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Avionics Design for Reliability

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March 1976

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on

Avionics Design for Reliability

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15. Abstract

Most of today's modern systems are dependent on the proper performance of a rather complex complement of electronic equipment. World technology has demonstrated that survivability related to reliability can be designed, predicted, monitored, tested and controlled. However, it is desirable to compare the expected total reliability programme cost with the benefits to be gained from having higher than essential reliability : some avionic failures will be catastrophic, some only critical, some of marginal importance. In every NATO Nation experts have the responsibility of choosing avionics equipment not only from the mission requirement standpoint, but also from the point of view of reliability. To satisfy this need, this Lecture Series on Avionics Design for Reliability was presented.

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Lecture Series No.81

AVIONICS DESIGN FOR RELIABILITY

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The material in this book has been assembled to support a Lecture Series under the joint sponsorship of the Avionics Panel and the Consultant and Exchange Programme of AGARD, presented in Munich, Germany on 5-6 April 1976, in London, UK on 8-9 April 1976 and at Griffiss Air Force Base, Rome, N.Y., USA on 13-14 April 1976.

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SUMMARY

Reliability is that intangible capability for future desired performance from a functional device. While it can be promised, certified, warranted, and guaranteed, its presence cannot be really verified without exploring or simulating future operating experience. The general public in choosing consumer products is vastly assisted in making selections by a particular product's public acceptance, acclaim, and by publicized repair and replacement experience, all this in areas of strong product competition. The buyers of a new and unproven product belong to the "let's-take-a-chance" fraternity and are closely observed by the preponderance of those in the marketplace and also by would-be product competitors. The years spent in achieving for a product the public recognition as the most reliable refrigerator, washing machine, or even automobile are so treasured and carefully protected that the smallest alteration in design to create a new model usually justifies unbelievable effort in life testing, trial production, field test, and other protection for the reliability reputation, for a high reputation, years in building, can be lost overnight.

The electronics field in general, and avionics in particular have made and are still making revolutionary progress in pushing forward the technical state-of-the-art. The almost total replacement of thermionic tubes by solid state devices, the astronomical expansion of computing capability, the tremendously successful exploitation of digital rather than analog design, all these when coupled with the influx of vast numbers of extremely enthusiastic and creative electronic designers have brought the wildest fantasies of technology seemingly within our grasp. All we need is more reliability which means even more money and extensive patience and thoroughness during design and development.

Much of the magnitude of the design problem seems to be created by the spread in breadth of the avionics state-of-the-art, more rapid than either hurried growth of academic capacity, or available apprenticeships and on-the-job learning. Unfortunately there has been too much of a market for innovative but incomplete design, design which achieves creditable performance only part of the time or unreliably. This basic problem is compounded by the high cost of new development— costs high enough to eliminate all customers save the military who have been conditioned over many recent years to accept less reliability than is tolerated by the public at large. But now it appears that this picture is changing.

The scarcity of funds for military procurement, and the publicity given to chronic unreliability problems are creating procurement demands for reliability guarantees, warranties, and life cycle cost studies.

The program covered by Lecture Series No.81 addresses and discusses problems of avionic unreliability. Described are typical methods for forcing reliability into new design and development, into new procurement requirements. Included are typical life cycle costs as affected by the reliability achieved. The case for improving initial designs with more background experience, greater patience and thoroughness by the designer is viewed as perhaps the soundest and in the long run the most economical means for reliability attainment. Case histories involving both reliability testing and field reliability achievement will be described. Of special interest is the opportunity to review problems and recommendations from a multi-national viewpoint.

As in previous Lecture Series, the last item on the program is a panel discussion which will give the audience the almost unlimited opportunity to further explore areas of special interest with any of the speakers.

AVIONICS RELIABILITY CONTROL DURING DEVELOPMENT

*George T. Bird
*G. Ronald Herd

SUMMARY

A comparison is made between actual reliability growth observed during recent years and the inherent reliability potential for avionics equipment. A method of control is presented integrating prediction procedures currently outlined in MIL-STD-756 and MIL-HDBK-217 with development testing. A nomograph is presented for determining the amount of design support testing which will be required to achieve a desired or specified value of avionics equipment reliability. The paper shows how these control procedures are used for specification, design planning, testing, and monitoring high reliability achievement in avionics equipment.

INTRODUCTION

Recently, reliability specifications established for a new generation of avionics equipment exceeded the achieved reliability by a factor of ten even though the achieved reliability was a 100% improvement over the preceding generation. The reliability desired for the next generation of avionics equipment will be even greater because of additional automatic and self-control features. To close this broad gap between requirement and achievement, a more concerted effort on reliability control during the R&D phase is needed.

System reliability in its operational role can be defined and measured in terms of at least two interdependent and intrarelated parameters -- functional performance and reliability. Actual measurement of reliability, as a composite of the functional parameters working in unison over time, has not been practicable until late in the development stage. However, it is now practicable to develop an accurate determination of the reliability potential of a given system design, based upon analytical and empirical "measurements" of individual parameters at critical decision points in both the concept formulation and the design phases. These measurements enable a manager to evaluate and control system reliability as an inherent "built-in" feature of the design in the very early formative stages of its evolution, when design deficiencies can be most economically discovered and corrected.

It is our belief that the required level of reliability can be systematically designed into an equipment if the designer is given the time, facilities, and management support required to specifically identify and circumvent the failure modes which, potentially, would jeopardize the inherent reliability of the design. Reliability of some of the more complex avionics system designs could be enhanced by as much as an order of magnitude, and more, if design verification encompassing design-proof testing were contractually stipulated and rigorously applied in acquisition programs.

RELIABILITY GROWTH HISTORY

An investigative study by Bird Associates assessed reliability growth in avionics systems over the past decade. The study consisted of a review of experience data accrued during a six-month period in 1970 on 98 generic types of avionics equipment used in a variety of aircraft. Of these, 35 types were procured with a contractually specified reliability requirement. Current reliability status of all 98 equipment types was determined on the basis of field data. A comparison was then made between the reliability status of this cross section of avionics equipment, which were operational in 1970, and the reliability of a cross section of operational avionics equipment which were studied in about 1958. This comparison was made to measure the reliability "growth" in avionics equipment design between the two operational periods and to evaluate the reliability potential which might be achieved in future acquisition programs.

The results of this study indicated that, on the average, an improvement of 2.3 to 1 in MTBF was achieved for those equipments procured with a reliability specification when compared to 1958 operational equipments. An improvement of only 1.6 to 1 was realized for equipments procured without a reliability specification when compared to 1958 operational equipments. The calendar time between these studies of 12 years is approximately 1.2 generations of system design, so a measure of equipment reliability growth per system generation is 100% (2:1) for those procured with a reliability specification and 50% (1.5:1) for those without specified requirements. Viewing this growth another way for new systems entering operational status each year, those procured with a reliability specification will have, on the average, an MTBF 7.2% greater than those of the previous year; for those procured with a reliability specification, the MTBF will be 4.0% greater than in the previous year's new systems. Since the contractually imposed reliability specifications did not require verification through demonstration testing, a 15% gain per year is potentially achievable, corresponding to a fourfold increase per generation.

Based upon the observed gains between 1958 and 1970 for the two methods of procurement, the reliability achievement of a typical operational avionics equipment is projected for a future point in time, illustrated in Figure 1. The expected MTBFs for typical operational avionics equipments in 1980 are detailed in Table 1 for three levels of complexity, under the assumption that the growth observed in the 1958-70 period is continued.

* Bird Engineering Research Associates Inc., Vienna, Virginia, U.S.A.

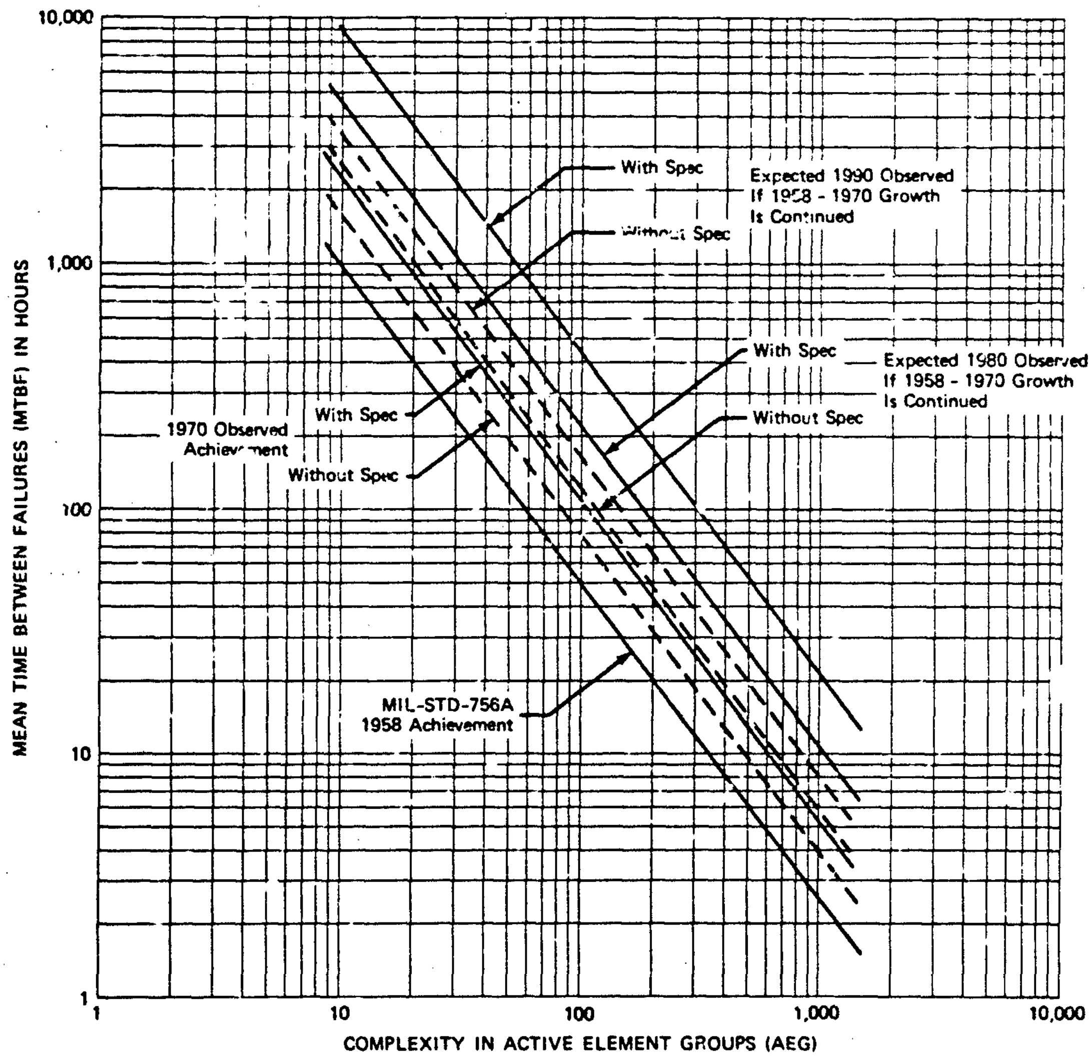

Figure 1. Avionics Equipment MTBF for Various Levels of Complexity Observed at Four Times for Different Types of Procurement

Table 1. Reliability (MTBF) Achievement Observed and Projected for Various Levels of Complexity (AEGs) for Procurement With and Without Reliability Specification

AEG	Observation Time			
	Observed MTBF 1958	Observed MTBF 1970	"Expected" MTBF 1980	"Projected" MTBF 1990
With Specification				
50		299	598	1196
100		115	230	460
200		46	92	184
500		13.8	27.6	55
1000		5.5	11	22
Without Specification				
50	130	208	312	468
100	50	80	120	180
200	20	32	48	72
500	6	9.6	14.4	21.6
1000	2.4	3.8	5.8	8.6

Extrapolation of the 4%, 7%, and 15% annual growth in MTBF postulated from the above analysis is presented in Figure 2 for a system with the equivalent complexity of 200 AEGs. This extrapolation through one generation does not extend to the region where constraints imposed by parts limitations, as indicated by MIL-HDBK-217, would invalidate the projection. From this projection, there is a range of 4:1 in the next generation MTBFs between tight "reliability-specification" acquisitions and those with no specified reliability.

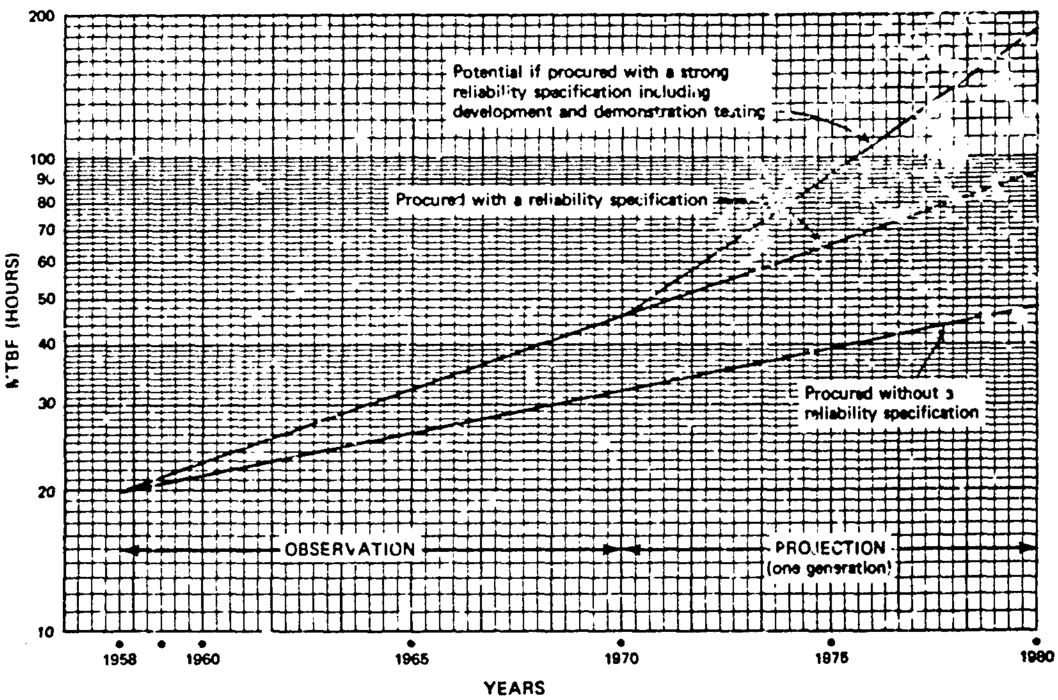

Figure 2. Reliability (MTBF) Achievement of a Typical 200-AEG Avionics Equipment in an Operational Environment Projected One Generation Under Different Procurement Rules

Evidence from field data indicates that current reliability maturity achieved in avionics equipment is about one-sixth of the specified MTBF (θ_0) requirement, averaged across the 35 equipments studied. By still another yardstick, MTBF of these 35 equipments (on the average) had achieved approximately one-tenth of their predicted MTBF (θ_p) as determined from MIL-HDBK-217 failure-rate analysis under the assumed airborne environment. Even though we have observed approximately 7.5% growth rate per year in equipment MTBF, it is clear that we have not come close to the reliability design potential of any given equipment with our initial design effort. We can improve this situation, however, through established reliability improvement procedures applied during the development phase -- before release of the prototype to production/deployment phases.

By monitoring MTBF growth during the development phase, we can make some projection on how much development testing would be required to achieve the specified MTBF requirement. How quickly a reduction in failure rate is achieved is a function of the effectiveness of the design/test/analysis team, since the test time required to achieve a given MTBF goal is a function of both the speed with which the failure rate can be reduced and the amount of failure-rate reduction required.

There are two general methods that can be used to increase reliability in the design of a system: (1) reduction of average stress through such efforts as parts selection, applications, load sharing, etc.; and (2) reduction in variability among failure mechanisms resulting in more homogeneity in the effects of stress. The first effort is usually resolved through analytical and empirical procedures, while the second usually requires empirical results from such things as development testing.

Consider, for example, the failure rates among failure mechanisms within an equipment, as illustrated on Scale A in Figure 3. The spread of failure rates is typical of what exists within a system. Design analysis usually shifts the total scale to the left or the failure rates to the right as shown by Scale B, and eliminates a few of the lower failure rates by designing out the failure mechanism, thus shifting that particular rate to the right. Development tests usually identify the higher failure rates (illustrated on the left) through repeated failure modes. Elimination or reduction of these modes by designing around the mechanism improves reliability. This is the key to high reliability that is usually overlooked in development programs.

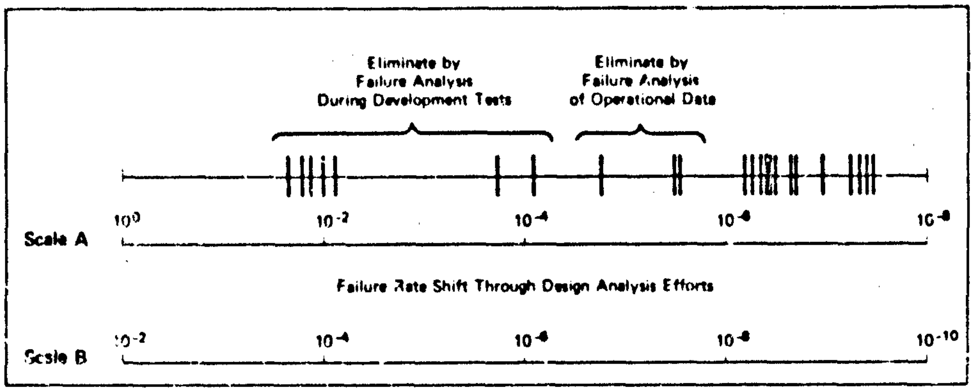

Figure 3. Example of Failure Rates Among Failure Mechanisms Within a System, and Identification of Those That Can Be Improved Through Testing

CONTROL OF DESIGN FOR RELIABILITY

Control of the design during development requires that a measure of the deviations from expected or desired be available to furnish the feedback for corrective actions. Sources of measured deviations include the following, among others:

- Quantitative design analysis
- Parts quality tests
- Inspections
- Burn-in tests
- Performance checks
- Development tests

Too frequently the information derived from these sources is not used to control reliability.

To control reliability achievement in the R&D phase of a system, the project manager must know how to perform three essential functions within the framework of his selected management approach:

(1) Contractually Specify the System Reliability Requirement. He must know how to specify realistic quantitative functional performance characteristics and design requirements for reliability relative to these performance characteristics, and how to specify demonstration test requirements and acceptance criteria to ensure conformance to the specified requirements.

(2) Evaluate Progress Toward the Specified Requirements. He must know how to evaluate design progress and problem status relative to specified system reliability requirements at designated design-review and critical decision points during the development phase, and how to verify the correction of deficiencies as a prerequisite to making a design approval decision.

(3) Verify Conformance to the Specified Requirement. He must know how to verify conformance to the specified reliability requirements and how to make accept/reject decisions at designated major milestones, on the basis of conformance verification test results, to ensure that system and equipment designs which fail to demonstrate conformance to specified system reliability requirements do not emerge from his program.

DEVELOPMENT TESTING REQUIREMENTS

In the design and manufacture of avionics equipment, many unknowns and intangibles exist that cannot be analytically forecast or foreseen. Extended product experience in the intended-use or simulated environment is necessary to identify the family of hidden failure mechanisms for corrective action and to validate corrective actions. The crux of reliability planning today is the ability to determine the amount of product experience (evaluation testing) needed.

The criteria for a successful development which satisfies reliability requirements consist of the following:

(1) Inherent reliability as measured by analysis (MIL-HDBK-217) must exceed the requirement; i.e., there must be a reliability design margin.

(2) Reliability growth experience must indicate realistic growth.

(3) Time for achievement must be available.

The successful program manager will satisfy these criteria by selecting a design through simplification, reduced parts stress, and other techniques in order to yield an inherent capability (MTBF) at least 125% of the required MTBF; making a realistic appraisal of the new design (initial reliability may be only 10% of the inherent); establishing a strong, disciplined analysis and corrective action team, and establishing testing schedules which recognize that growth in reliability will be inversely proportional to the cumulative operating (test) time.

The amount of "effort" required to achieve a specified MTBF depends on three items -- the specified MTBF (θ_0), the initial MTBF (θ_1), and the rate (m) at which the MTBF can be increased, as illustrated in Figure 4. The difference between the inherent reliability which represents the potential reliability for the system and required reliability is the design margin.

The relationship among test time, the growth rate, and the requirements is given by the following:*

$$t^m = (1 - m)\theta_0/\theta_1$$

where time is expressed in standardized units of θ_p (the potential MTBF);

m is the growth rate;

θ_0 is the required MTBF; and

θ_1 is the initial MTBF measured from test data.

This theoretical relation, which has been confirmed empirically, reflects the relation found between cumulative test time and mean time between failures. This expression can also be written as

$$t^m = (1 - m)K_1/K_0$$

where $K_1 = \theta_p/\theta_1$ is the reliability maturity ratio, and

$K_0 = \theta_p/\theta_0$ is the reliability design margin.

Plotting this relation on log-log paper results in a straight line, which allows simple comparisons between expected and observed. The growth rate, m, has been determined from the study of reliability growth in a variety of equipment; these determinations are shown in Table 2 along with typical reliability maturity ratios. A large value for m ($m > 0.5$) reflects a hard-hitting, aggressive reliability program with management support spanning all functions of a knowledgeable organization, while a low value of m ($m < 0.1$) reflects the growth in reliability that is due largely to the need to resolve obvious problems that impact on production, and to corrective action resulting from user experience and complaints. We have actually observed negative values in certain situations where engineering changes had been introduced to improve "performance", at risk of loss in reliability. The maximum value of m that could be expected is probably no greater than 0.6 or 0.7 because of the time lag in detecting failure mechanisms, creating solutions, and implementing the engineering changes. Our experience during development testing indicates that realistic values of m are in the 0.35 to 0.50 range.

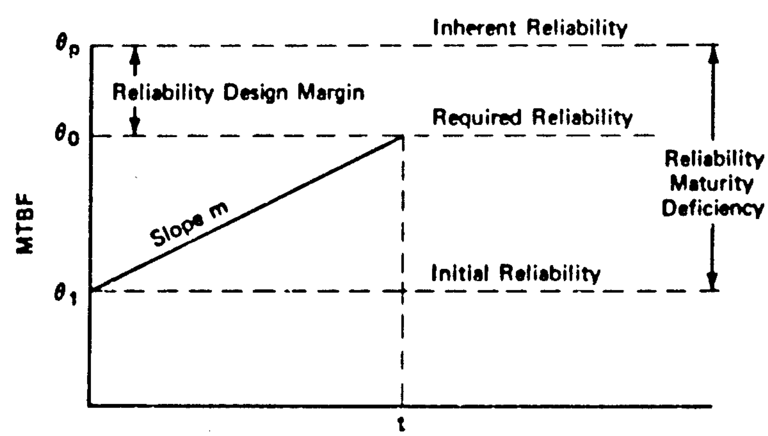

Figure 4. Relationships Among Specified MTBF (θ_0), Initial MTBF (θ_1), and Growth Rate (m)

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*J. T. Duane, "Learning Curve Approach to Reliability Monitoring," IEEE Transactions Aerospace, Vol. 2, March 1974.

G. Ronald Herd, "The Relation Between Test Time and MTBF Under a Changing System Failure Rate During System Testing," Bird Engineering-Research Associates, Inc., 1975.

Table 2. Sample of Test Parameters Observed in Actual Test

Equipment/System Function	Complexity (AEGs)	Test Conditions or Life Cycle Phase	Observed Values	
			Maturity Ratios, K_1	Growth Rates, m
Low Power Electronic Units				
Analog (receivers, amplifiers, etc.)	200-600	Contractor Development Test	6	0.49
Analog Computer	400-600	Fleet Operational (ORDALT)	15	0.20
Digital Computer	3000-6000	Contractor Development Test	4	0.48
High Power Electronic Units				
Analog (power supplies, microwave amplifiers, etc.)	200-1000	Contractor Development Test	10	0.30
Traveling Wave Tube (in development)	50	Vendor Life Test	10	0.65
Radar Equipment				
Pulse Transmitter (new)	1000-1500	Contractor Development Test	20	0.35
Pulse Transmitter (old)	1000-1500	Fleet Operational (ORDALT)	35	0.30
Continuous Wave (CWI)	400-600	Contractor Development Test	15	0.35

Using the relation discussed above, we can now determine, for planning purposes, the testing time required to achieve the reliability requirement. A nomograph,* shown in Figure 5, has been developed to simplify the determination of expected test time required, given the reliability design margin ($K_0 = \theta_p/\theta_0$), the reliability maturity ratio ($K_1 = \theta_p/\theta_1$), and the growth rate (m).

Assume, for example, a contractor enters the development phase with an equipment design whose predicted MTBF was determined to be $\theta_p = 100$ hours based on MIL-HDBK-217 failure-rate stress analysis. Also assume the specified MTBF requirement for the equipment had been established at $\theta_0 = 80$ hours. These two values yield a reliability design margin of $K_0 = \theta_p/\theta_0 = 100/80 = 1.25$. If, after the first 100 hours of development testing (i.e., at $t_1 = 1 \times \theta_p = 100$ hours), ten critical and major failures had been observed (i.e., $r_1 = 10$), then the initial MTBF, $\theta_1 = t_1/r = 100/10$ is 10 hours. From this, the reliability maturity ratio, $K_1 = \theta_p/\theta_1$, is determined to be 10. The development test program will require between 1,600 hours (for m = 0.5) to 31,000 hours (for m = 0.3), depending on the contractor's effectiveness in identifying and correcting failures during the test.

The following guidelines can minimize the amount of development testing required to achieve a specified value of MTBF:

(1) Provide an MTBF Design Margin. Achieve a design goal MTBF (as verified by prediction analysis) well above the specified MTBF. A reliability design margin (between specified requirement and the inherent predicted goal) of between 25% and 50% (i.e., $K_0 = 1.25$ to 1.5) should be sought.

(2) Perform Design Review and Configuration Analysis Prior to Release to Development. Verify adequacy of the item (e.g., equipment) to be submitted for development testing to verify compatibility of stress ratings and tolerances, quality of parts and materials, quality of workmanship, etc. This helps to reduce the reliability maturity ratio, $K_1 = \theta_p/\theta_1$, which is measured during development testing.

(3) Assign and Follow Up on Corrective Action. Require that all failures observed during development testing are fully described, recorded, diagnosed, and formally assigned for corrective action. Then systematically follow up and verify completion of each corrective action assignment. The goal is to achieve an MTBF growth rate to approach (or exceed) m = 0.5.

The grid in the center of the nomograph shown in Figure 5 combines the two experience variables (K_1 and m) through which K_0 and T_0 are related. Both values of K_1 and m must be established on the basis of previous test experience; or, in the absence of experience, a conservative estimate can be derived from other closely related test experience, as tabulated in Table 2.

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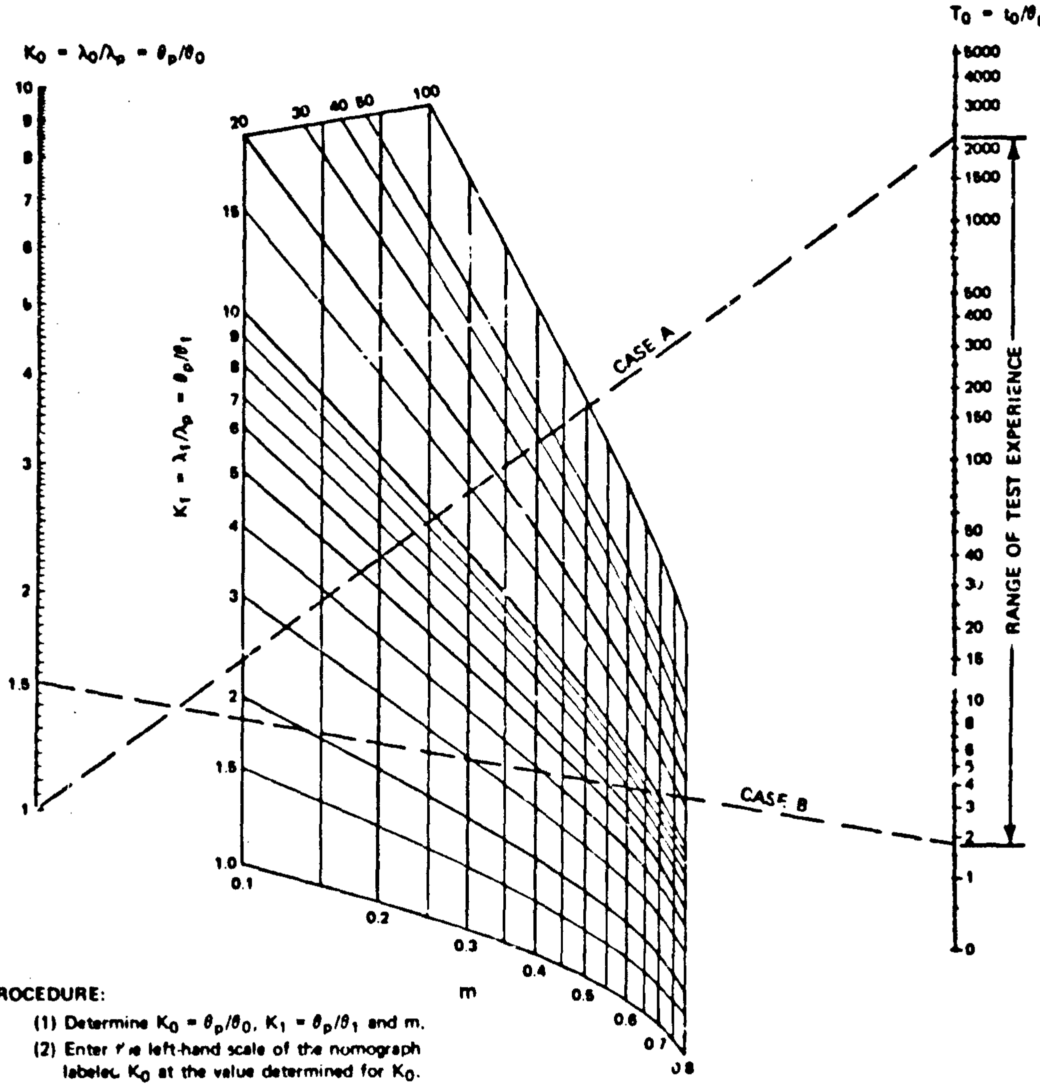
* George T. Bird, "Development Testing Requirements To Achieve Reliability Requirements," Bird Engineering-Research Associates, Inc., 1974. Also published in Reliability Guides, NAVORD OD 44622, Vol. 2, Naval Sea Systems Command, 1976.



PROCEDURE:

(1) Determine $K_0 = \theta_p/\theta_0$, $K_1 = \theta_p/\theta_1$ and m.

(2) Enter the left-hand scale of the nomograph labeled K_0 at the value determined for K_0.

(3) Enter the center mesh at the point of intersection of the curves determined for the values of K_1 and m.

(4) Join the K_0 point and the K_1 and m intersection point with a straight edge and extend it through the right-hand scale labeled T. Read the test time ($T = t/\theta_p$) at the intersection of the straight edge with the right-hand scale.

Figure 5. Nomograph for Determining Development Test Time (T) Required To Achieve a Specified Value of MTBF or Failure Rate

Two cases are used to illustrate use of the nomograph

- Case A -- an equipment whose design MTBF margin was zero (e.g., $K_0 = 1.0$), with a high reliability maturity ratio indicating inadequate design and configuration review prior to release to development (e.g., $K_1 = 15$), and in which development testing proceeded without a strong reliability assurance (follow-up) program (e.g., $m = 0.3$).
- Case B -- an equipment with 50% design MTBF margin (e.g., $K_0 = 1.5$), an adequate final design configuration review prior to release to development (e.g., $K_1 = 5$), and an effective reliability assurance program throughout development (e.g., $m = 0.5$).

Assume that both Case A and Case B had been designed to satisfy the same specified MTBF = 100-hour requirement. Case A will require approximately 25,000 hours of development testing to achieve the specified MTBF. In contrast, Case B will require approximately 300 hours of testing to achieve the same requirement. The range in test time (between Cases A and B) shown in Figure 5 closely corresponds to the test experience over many test programs.

The effect of a high reliability design margin on the expected development test time is illustrated in Table 3. Increasing the margin by 20% (from 1.25 to 1.50) reduces the expected test time by 36.6%, as indicated in the table, and an increase of 40% (from 1.25 to 1.75) yields a reduction of 56.8% in expected test time. Doubling the margin (from 1.25 to 2.50) reduces test time by 82.4%.

Table 5. Development Test Time for a Typical Situation for an Avionics Equipment ($\theta_p/\theta_1 = 10$; $m = 0.4$)

Reliability Design Margin θ_p/θ_0	Expected Development Test Time $t = [(1 - m)\theta_0/\theta_1]^{1/m}$
1.00	$88.2 \times \theta_p$
1.25	$50.5 \times \theta_p$
1.50	$32.0 \times \theta_p$
1.75	$21.8 \times \theta_p$
2.00	$15.6 \times \theta_p$
2.50	$8.9 \times \theta_p$

MONITORING RELIABILITY DURING DEVELOPMENT TESTING

The relation among failures (critical and major), test time, initial value of observed MTBF, and the effectiveness of the contractor's reliability assurance program was presented earlier. These measures can be combined to provide a graphical method for monitoring reliability status throughout the development test program and provide:

- Current status of MTBF relative to established milestone criteria.
- MTBF growth rate.
- Test time required to achieve the specified MTBF.
- An estimate of the MTBF that will be achieved at the end of the currently planned test program.

Experience, covering many test programs, has revealed a relation between the (logarithm of the cumulative test time and the (logarithm of the) cumulative number of failures when corrective actions are taken to eliminate failure modes.

There are four ways we may monitor the information that is generated during a test program; each involves presenting the number of failures or some function thereof against the cumulative test time. The four measurements, illustrated in Figure 6, are:

- Cumulative number of failures.
- Cumulative MTBF.
- MTBF achieved at a particular point in time, the instantaneous MTBF.
- MTBF during the last k time units, moving average MTBF.

To develop the expected values against which progress will be measured and to establish the test program duration requirement, we return to the relation:

$$t^m = (1 - m)\theta_0/\theta_1$$

From this relation, we can determine the expected growth in reliability and thereby the standards against which the four measurements identified above are compared.

Cumulative Number of Failures

The cumulative number of failures expected during the accumulation of test time is given by

$$r = r_1 t^{(1-m)}$$

where r is the number of failures observed during development testing;

t is the test time expressed in θ_p's (inherent MTBF);

m is the measure of growth in reliability; and

r_1 is the number of failures observed during the first θ_p hours of development testing.

The value of m and r_1 should reflect the developer's own experience, but if that is not known, typical values of $m = 0.4$ and $r_1 = 10$ may be used to establish growth objectives so that the expected number is $r = 10t^{0.6}$. Updating of r_1 can be accomplished at the end of θ_p test hours. Thus, the comparison of achievement against expectation can be monitored by plotting the number of failures against the total test time on log-log paper as illustrated by Curve 1 on Figure 6.

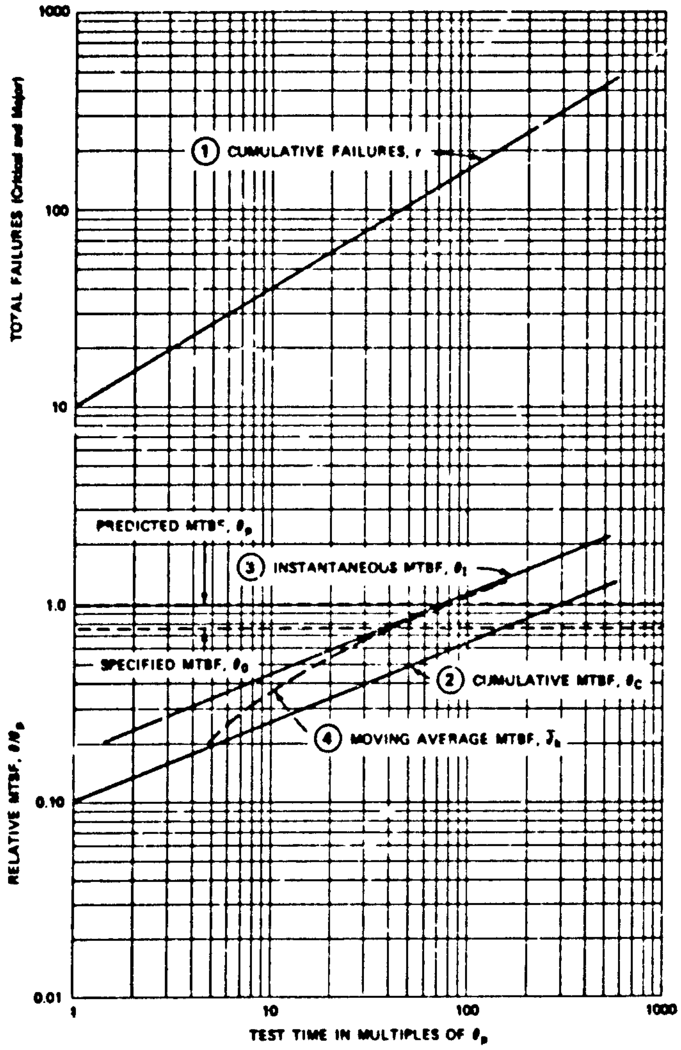


Figure 6. Four Ways of Presenting Failure Data for Reliability Monitoring

Cumulative MTBF

The cumulative MTBF, illustrated as Curve 2 of Figure 6, is the cumulative time, t, divided by the cumulative number of failures, r; and using the above expression for r, then expected cumulative MTBF can be written as:

$$\theta_c = \theta_1 t^m$$

where t is the development test time;

m is the reliability growth rate; and

θ_1 is the MTBF observed during the first unit (θ_p hours) of testing time.

The value of m and θ_1 used to establish the program objectives should reflect the contractor's own experience; however industry experience can be used with $m = 0.4$ and $\theta_1 = \theta_p/10$ so the MTBF to be expected during development testing is given by $\theta_c = (\theta_p/10)t^{0.4}$. This expected cumulative MTBF can be plotted on log-log paper as a straight line (see Curve 2 of Figure 6). By plotting the observed MTBF (t/r) as the development testing progresses, a comparison may be made between the objective and actual achievement.

Instantaneous MTBF

With corrective actions changing the MTBF of the system during development testing, the cumulative MTBF will be influenced by the "lower" MTBFs attained during the early test period. To determine the achievement in MTBF at a particular point in test time, the derivative of the cumulative MTBF -- the instantaneous MTBF -- should be monitored. The instantaneous MTBF can be shown to be $\theta_I = \theta_c/(1 - m)$, and we can plot the expected instantaneous MTBF when θ_c and m are known. Since it is not possible to observe the instantaneous MTBF, we can only approximate it by observing the MTBF over the last unit of test time (θ_p hours). The expected instantaneous MTBF can be plotted also on log-log paper for ease in comparison, as shown by Curve 3 of Figure 6. The observed MTBF during the last unit of test time can then be plotted for control purposes.

The observed MTBF for the last unit of test time will be based upon few failures; and as the attained MTBF approaches the required MTBF (θ_0), the variability in observed value will increase and it may become difficult to interpret or determine the true achievement.

MTBF During Last k Time Units (Moving Average MTBF)

Since the "observed instantaneous" MTBF is highly variable, particularly when the actual attained MTBF approaches the required MTBF, it is advantageous to use a longer test period to establish the attained MTBF and still be more indicative of the achieved status than the cumulative MTBF. Therefore, for monitoring purposes, we can use the last k units of test time to determine the MTBF; and, for a fixed k, the base period of test time continually moves as the test time progresses, yielding a moving average. The expected "moving average" MTBF is given by:

$$\bar{\theta}_k = \theta_1 t^m \left[\frac{(k/t)}{1 - (1 - k/t)^{1-m}}\right] = \theta_c \left[\frac{(k/t)}{1 - (1 - k/t)^{1-m}}\right]$$

where $\theta_1 = \theta_p/10$ and $m = 0.4$, based upon industry experience; it is plotted for $k = 5$ in Curve 4 of Figure 6. It can be shown that $\bar{\theta}_k$ approaches the instantaneous MTBF as $t \to \infty$ (since k is fixed).

To monitor progress then, we can compute the MTBF for the last k units of time and plot this against total test time on log-log paper for a simple comparison between expected and actual achievement.

Example

Now we can utilize the information presented above in the following example of development testing results. In this example, engineering changes were made during testing wherever failure mechanisms were identified and solutions established. The system under test had an inherent MTBF of 100 hours and the required MTBF was 80 hours. Prior to the start of development testing, the expected growth and required test time were established based upon industry experience that the initial MTBF would be 10% of the inherent MTBF and that growth rate in reliability would yield an $m = 0.4$. Table 4 presents the actual observed values determined from the test results, and these data are shown in Figure 7 plotted against the expected values established in advance of testing. Comparison of actual against expected results as shown in the figure furnishes the monitoring capability for reliability control.

Table 4. MTBF Calculations as Failures Occur in Development Testing

100-Hr Test Periods Ordered	No. of Failures Obsvd	Cum. Test Time t	Cum. Failures r	Cum. MTBF θ_c	Instantaneous MTBF θ_I	Moving Average MTBF $\bar{\theta}$	Growth Rate m
1	11	100	11	9.1	9.1		
2	4	200	15	13.3	25.0		0.56
3	5	300	20	15.0	20.0		0.46
4	4	400	24	16.7	25.0		0.44
5	3	500	27	18.5	33.3	18.5	0.44
6	3	600	30	20.0	33.3	26.3	0.44
7	3	700	33	21.2	33.3	27.3	0.44
8	2	800	35	22.9	50.0	33.3	0.44
9	2	900	37	24.3	50.0	38.5	0.45
10	3	1000	40	25.0	33.3	38.5	0.44
11	2	1100	42	26.2	50.0	41.7	0.44
12	2	1200	44	27.3	50.0	45.5	0.44
13	1	1300	45	28.9	100.0	50.0	0.45
14	2	1400	47	29.8	50.0	50.0	0.45
15	1	1500	48	31.3	100.0	62.5	0.46
16	2	1600	50	32.0	50.0	62.5	0.45
17	2	1700	52	32.7	50.0	62.5	0.45
18	2	1800	54	33.3	50.0	55.6	0.45
19	1	1900	55	34.6	100.0	62.5	0.45
20	2	2000	57	35.1	50.0	55.6	0.45
21	1	2100	58	36.2	100.0	62.5	0.45
22	2	2200	60	36.7	50.0	62.5	0.45
23	2	2300	62	37.1	50.0	62.5	0.45
24	3	2400	65	36.9	33.3	50.0	0.44
25	2	2500	67	37.3	50.0	50.0	0.44
26	2	2600	69	37.7	50.0	45.5	0.44
27	1	2700	70	38.6	100.0	50.0	0.44
28	2	2800	72	33.9	50.0	50.0	0.44
29	1	2900	73	39.7	100.0	62.5	0.44
30	1	3000	74	40.5	100.0	71.4	0.44

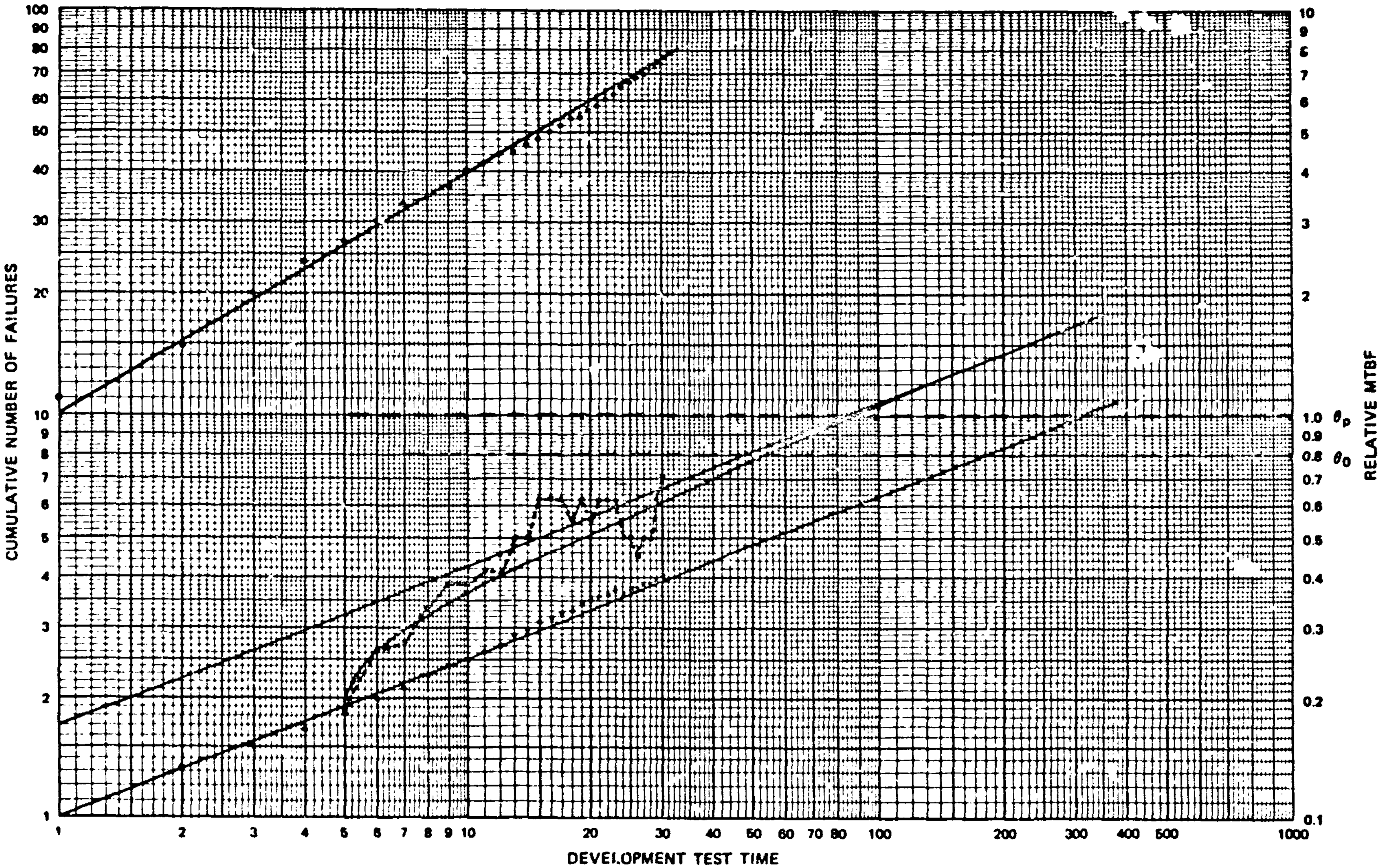


Figure 7. Comparison of Expected and Actual MTBF Achievement, To Monitor Reliability Control

RELIABILITY GROWTH MODELLING FOR AVIONICS

by

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SUMMARY

The factors which influence the reliability of avionics are reviewed, with emphasis on the development phase. Reliability growth modelling is increasingly being recognised as a realistic technique for management to use in project planning, and a method for providing progressive estimates of reliability achievement during the development phase. Reference is made to the use of computer programmes for these purposes, and for estimating costs.

The validity of the Duane Model is considered against practical experience gained during development of military avionics. Explanations are given for observed deviations in the short and long term periods, and the need to make adjustments for different environmental stress conditions is noted. Further verification of a mathematical law for the rate of appearance of types of systematic (pattern) failures is reported.

The paper concludes with a review of potential avionic reliability as more microelectronics are used, and considers the eventual limiting factors.

INTRODUCTION

The interest in reliability growth modelling for avionics really began in 1968 when Codier presented a paper at the IEEE Annual Symposium on Reliability[1], and drew attention to an empirical model which J.T. Duane had proposed six years earlier in a General Electric Technical Report - See Appendix 1.

The original data had been derived from test experience with complex aircraft generators, hydro-mechanical devices and a jet engine - see Fig 1. Duane had observed that for test programmes in which a sustained effort was maintained to introduce improvements following experience of failure, there was a mathematical relationship between overall failure rate counting all failures, and total operating time, such that plots on log-log paper lay approximately on a straight line. Codier reported the same law for data obtained during the development of an airborne radar. Then in 1970 Selby and Miller of the same company presented their well known paper[2] in which Duane's Model was shown to apply equally well for several avionic equipments.

The increasing current interest stems mainly from the facility of providing management with progressive estimates of reliability achievement based on actual operating experience and an indication of the prospects of eventually meeting the reliability target within the allotted resources. The real merit of this modelling approach is that it requires a planned and disciplined test programme aimed at searching out the weaknesses in a new equipment. The programme does not diminish the responsibility of the designer in any way.

The increasing emphasis on reliability stems from the very high cost of procuring and operating modern military aircraft. Any successful sortie is now more dependent than ever before on the reliability of highly complex avionics. The costs attributable to the maintenance and support organisation on account of unreliability are alarmingly high. In the 1971 AGARD Lecture Series it was stated by Baker[3] that the aircraft operating and maintenance costs over a ten year life period were typically three times the initial cost. The remarkable advances in electronics technology have meant that each generation of aircraft has been fitted with radically different and more sophisticated equipment, and in much greater quantity. The reliability of the circuit elements has probably increased by at least an order over the last fifteen years, but there has been no corresponding reduction in the contribution of avionics to the unreliability of the total aircraft system.

It is only fair to point out that there has been some opposition to the Duane Model. Some don't care for the empirical nature of the model, some fear the possibility that the reliability estimates might be accepted in lieu of a formal compliance test at the end of development or in production. This paper will consider experience including anomalies that have been observed, in order to promote further discussion on the subject.

FACTORS INFLUENCING RELIABILITY

In order to complete the setting of the scene, Table 1 lists the more important of the many factors that influence the reliability of military avionics.

1.	Requirement of highest performance for military advantage, often resulting in complexity
2.	Quality of design
3.	Use of latest components and constructional techniques
4.	The aircraft factors; type of aircraft, installation, sortie duration, adverse operational environments
5.	Resources allocated for development; timescale and money
6.	Contractor awareness of reliability engineering
7.	Number of development models
8.	Total operating time during development
9.	Intensity of monitoring performance, investigating deficiencies and taking corrective actions
10.	Quality control in manufacture, including burn-in
11.	Training of Services personnel
12.	Maintenance standards and test facilities

TABLE 1

It might be claimed that good management should take care of all these factors, however at the start of a project almost everyone is optimistic. There is a readiness to believe that the anticipated potential problems will be solved and that the latest laboratory discoveries can be perfected and turned into a production item despite any constraints of time and money. Experience shows that many of the weaknesses that eventually cause unreliability in service have often not been foreseen, and have not been experienced during the development phase. It follows therefore that quality of design must be given greater attention, and that there must be an extensive reliability test programme during development in order to discover the latent weaknesses.

It is most important to staff the test activity with engineers who have had design experience, and to provide comprehensive test equipment with which they can monitor performance in depth. It is also important to have a data collection centre and to ensure that every indication of weakness in every development equipment is reported. The data centre, staffed by reliability engineers, is responsible for ensuring that every report is referred back to the appropriate department and that the agreed decision on follow-up action is recorded and implemented.

U.K. EXPERIENCE OF RELIABILITY GROWTH MODELLING

I was in the audience at Boston when Codier read his paper and my interest was aroused. On returning to the U.K. a retrospective analysis was carried out on data from the development programme for an airborne radar, and it was found that the plots fitted well to Duane's Model - see Fig 2. In this graph cumulative MTBF has been plotted instead of cumulative failure rate. It shows how the attained or "instantaneous" MTBF, that is the MTBF which should be exhibited if no further modifications were introduced, is obtained by simply multiplying the cumulative observed MTBF by $\frac{1}{1-\alpha}$, where α is the tangent of the angle on the log-log paper. Plots of the attained MTBF will lie on a parallel line as shown, and by extending this line a prediction can be made of the further improvement that should be realised as the test and modification procedure continues. In this case a further 800 hr of severe environmental test should result in the incorporation of improvements which will raise the MTBF from 61 to 70 hr.

At this point it is worth noting that occasionally there is a misunderstanding about the parameter α, which has always been called the "growth rate" in Duane terminology. This is a misnomer and "growth slope" might have been more appropriate. Since α tends to be constant, some think at first sight that the rate of improvement of MTBF will remain constant as more operating hours are accumulated. This is not so, and the rate of increase of MTBF is actually proportional to (operating time)$^{\alpha-1}$, therefore it diminishes with increasing time - See Appendix Eq. (6).

Data from two more U.K. projects showed reasonable agreement with Duane's Model, with "growth rates" of 0.4 and 0.5 approximately, the latter reflecting advanced new technology. Fig. 3 shows data for two development models of an airborne radar operated simultaneously in a severe test environment. The operating hours and number of failure have been totalled. The growth rate α after 2800 hr was 0.41, which was close to the figure of 0.4 that had been anticipated initially after an assessment of the technical difficulties involved in the project, and previous experience with the same contractor. The early reliability standard was slightly below that predicted, but in general the reliability growth plot showed good agreement to the path that was predicted in 1972, up to about 3000 hr. Over the last 2000 hr the plots have deviated from the previous straight line, reducing α slightly to 0.38 and causing a deviation in the line for the attained MTBF, which has reached 100 hr compared with the 120 hr target. However it is thought that this estimate is somewhat pessimistic because a number of repetitive failures have been included, and this problem with Duane estimates will be referred to again later.

Practical aspects of a reliability growth programme will now be considered in three periods, the early time period of the first few hundred hours, the middle period, and the later period after several thousand hours.

The Early Time Period

After an equipment is first assembled, it has to go through a period of operation in order to identify and eliminate any manufacturing errors and to confirm that it is working satisfactorily. The equipment is then passed to the reliability test section, where it is operated typically for a further 50 hr at room ambient, followed by a further 30 hr during which separate tests are carried out under vibration, and at high and low temperatures. This is a familiarisation exercise for test procedures, a burn-in process, and an expeditious procedure for clearing the more obvious deficiencies associated with exposure to one particular environment. The equipment is then considered ready to start the accounted reliability growth programme. It will have operated for about 100 hr in all since assembly.

The first Duane plot is made after a further 100 hr operation. This is the same convention as that adopted by Selby and Miller[2]. In the early accounting period the plots tend to be somewhat erratic, but as testing continues and improvements are introduced they become orderly and the familiar straight line on log-log paper begins to appear. In our experience if the line is extrapolated back it intersects the 100 hr axis in the region of 15% of the predicted MTBF. Selby and Miller reported 10%, and the range 10-20% appears to cover nearly all known cases.

With the first development models on a new project, another trend has been observed when plotting Duane charts, as shown in Fig. 4. The dip is associated with the phase when an increasing proportion of the operating time is under a severe test environment. This observation leads to some important practical considerations. Firstly, when investigating the cause of a failure which has occurred at low or high temperature, the engineers often have to operate the equipment experimentally at room temperature, and sometimes the investigation may be prolonged. If further failures occur, perhaps unrelated to the one under investigation, these have to be counted in the cumulative total. But if the environmental stress level is low, the failure rate should be lower than that when the equipment is subjected to a severe test condition. It seems logical to propose that operating time should be normalised to a standard environmental stress level. This will largely eliminate the dip in the graph shown in Fig. 4. Another factor although minor which contributes to the dip is that delays sometimes occur before a modification is finally decided. There is pressure to keep up with the schedule for accumulation of operating hours, and incorporation of modifications is often delayed until the test is stopped by some other event. Thus there is a reaction time before the effect of corrective actions begins to show on reliability growth. This is particularly so in the early time period when the failure incidence is higher. Duane assumed that any modifications would be introduced promptly.

The Middle Time Period

For the major middle time period from a few hundred out to several thousand hours the Duane Model fits well in our limited experience, and is most useful in providing practical quantitative evidence to management on the rate of progress towards meeting the reliability requirement.

Two points are worth noting. The first is that there has been some evidence that reliability is influenced by the rate of accumulation of operating hours. Higher reliability appears to be associated with faster accumulation of operating hours in a given calendar period. The evidence tends to be masked by the smoothing effect of cumulative plots. One explanation could be the presence of a non-operating failure rate. The second point is that failure incidents tend to bunch together.

The Later Time Period

In the later time period after several thousand hours of operation, plots usually begin to deviate below the extrapolation of the previous straight line, indicating that the "growth rate" α is beginning to decrease. As an illustration, in the case of the results for the airborne radar project shown in Fig 3, the deviation was partly due to repetitive failures caused by two very difficult problems which persisted until nearly the end of the test programme. In such cases estimates of attained MTBF tend to be low because both cumulative MTBF and α are reduced. Some adjustment in the number of failures may be considered when there is no doubt that the problem has been overcome.

It is suspected that some latent secondary failures occur, that is failure of components which were subjected to overstress when earlier equipment failures occurred, sufficient to cause some damage but not to show up as an equipment malfunction. For example, suppose a semiconductor device fails after 2000 hr of severe environmental testing for no apparent reason. It may be difficult if not impossible to prove that it had been subjected to an electrical overstress. It might have been a sub-standard component initially, but burn-in plus 2000 hr seems a long time to have functioned without any indication of trouble. The risk of secondary damage must be a possibility.

Practical experience does suggest that the Duane graph will tend to flatten out eventually for complex avionics because of the persistence of some failures which are related to technical difficulty, also our inability to ensure 100% quality in components and construction, and the occasional cases of accidental overstress. A good example is the high voltage transmitter and associated power supplies of an airborne radar. Bezat et al[4] also observed this deviation in the plots during the later time period, and in order to overcome the difficulty proposed that a random failure rate term should be added to the Duane equation.

THE EXPONENTIAL LAW FOR SYSTEMATIC FAILURES

N.B. Systematic failures are equivalent to pattern failures and are repetitive or by nature likely to be repetitive. They are identified as due to design or manufacturing weaknesses and are capable of being demonstrated by intent.

An empirical law for the rate of appearance of types of systematic failure was reported in my joint paper with Mr P.H. Mead at the 1969 IEE Reliability Symposium[5] - see Fig 5. For several build standards

of a complex airborne radar, subjected to a fairly severe environmental test cycle (-26/+70°C cycling, with extensive swept frequency vibration 10-200 Hz at 1.7g), the following law was discovered:-

$$F_{tso} = F_{tsp}\ (1 - e^{-t/400})$$

where F_{tso} = number of types of systematic failure observed in t operating hours,

F_{tsp} = total types of systematic failure present.

The 400 figure is an empirical time constant for the stated environmental test conditions. For less severe conditions it should increase, and conversely decrease for more severe conditions, in the limit tending to zero for a high overstress accelerated test condition. Experience indicates that the figure of 400 applies consistently for the typical thermal cycling tests with vibration that are used in the development phase for military avionics. The formula indicates that over 90% of the types of systematic failure present in any sample equipment will be revealed in approximately 1000 hr ie $(1 - e^{-1000/400})$. It is necessary to continue for a further period of time to confirm that modifications are satisfactory, but in general it appears that 1500-2000 hr might be a practical limit for each model unless the target MTBF is at least several hundred hours, or there is a case for observing long term wearout failures. It is more rewarding and in most cases more cost effective to commence tests on a new equipment of improved build standard.

More information about the ultimate limitations of the otherwise discarded models could be obtained by carrying on with a deliberate overstressing programme. The overstressing could be either thermal or mechanical or electrical, and would require close collaboration with the designers in order to provide the most useful information. The time constant would then be less than 400.

Now from the mathematical aspect this exponential law is not compatible with Duane's Model. By differentiating, it is apparent that log of failure rate will be proportional to time, and not log time. It follows that if the Duane plots lie on a straight line on log-log scales, there must be additional failures to those classified as Types of Systematic, and these are:-

a) Repetitive systematic failures where the complete cure has not been found.

b) The so-called random failures where the cause cannot be traced; these include possible latent secondary failures.

c) Long term failures identified as due to quality control lapses eg Sub-standard components and poor assembly.

d) Wear-out failures eg Magnetrons.

It is most interesting that the numbers add up to give a good fit on the log-log Duane Plot while the rate of appearance of Types of Systematic Failure consistently fit the exponential law.

Fig 6 shows data for an early development radar on a current project. It should be explained that our policy is to record every observation that might indicate a deficiency in the new equipment, and to check that corrective action is taken whenever possible. Every event is classified according to the effect it would have had in operational use of the equipment, for example whether it would have caused a mission failure, or whether it would have necessitated unscheduled maintenance when the aircraft returned to base. In less than 10% of the events is there any doubt about classification. The graphs show that 63 types of systematic defect were observed on the radar and that 30 types would have caused an aircraft mission failure. The figures are related to the quality of design, the technical difficulty and the manufacturing standards. The defect/mission failure ratio is useful advance information for the Services about the new radar.

This exponential law seems to apply consistently, and for different categories of events. It has also been observed that at least two-thirds and sometimes four-fifths of the deficiencies found during development or in service use cannot be identified at the stage when the first hardware is assembled. These weaknesses are not foreseen by anyone at that stage, and at least one third of them have nothing to do with the electronic components or circuit design and are mainly mechanical weaknesses. This emphasises the quality of design factor. Computer-aided design shows some signs of improving the situation.

THE ENVIRONMENTAL STRESS FACTOR

In recounting the experience of a dip in the early Duane plots, attention was drawn to the variation of reliability with ambient temperature, and the desirability of normalising operating time to a standard environmental stress level.

A scaling factor can be derived from Fig 7 which plots failure rate against component ambient temperature. For example, operating time at 80°C would be multiplied by three in order to normalise to time at 20°C ambient. The overall effect of temperature on equipment failure rate has been calculated for positive Centigrade temperatures using MIL HDBK-217A/B data on components. It is believed that failure rates also increase with decreasing sub-zero temperatures, because mechanical stresses in parts increase due to the different expansion coefficients of materials and the higher moduli of elasticity. It is valid to assume a standard curve because the percentages of resistors, capacitors, active devices etc are fairly consistent for most equipments.

There is little agreed information about the influence on reliability of other environmental stresses such as humidity and rate of change of temperature. In assessing the results from growth programmes where it is usual to apply severe environmental stress cycles, the Services want to be informed about the predicted reliability under typical user conditions which are usually less severe. We agree scaling factors for reliability to allow for differences in the environmental stresses before the

programme starts, admittedly against limited data. Even in the case of MIL-STD-781B testing there is apparently a lack of agreement about such scaling factors for environment. This is a subject which deserves more attention by reliability engineers.

On one project an unusual environmental test cycle has been used, as shown in Fig 8, where the equipment operating cycle is not in phase with the temperature cycle. The effect is to subject the equipment to varying rates of temperature change and varying humidity conditions. Switching operations take place at various temperatures. The temperature cycle is changed at monthly intervals, one month from room temperature to +70°C, the next from room to -26°C. All this is done in order to enhance the chances of showing up the deficiencies in the design and manufacture, and in the operating procedures. It does provide some similarities to the changing conditions that will occur in aircraft use, although the temperature range is increased. On this project it was provisionally agreed with all parties concerned that reliability standards observed using this test cycle would be doubled to provided estimates for reliability after settling down in service. Time will tell how good or bad this assumption was!

PROGRAMME PLANNING USING GROWTH MODELS

The use of the reliability growth model concept in programme planning was a natural corollary and it has made a valuable contribution by focussing attention on the importance of providing specific equipments for long term testing. Fig 9 illustrates planning for a radar with a requirement for 250 hr MTBF.[6] Three radars were allotted and a cumulative operating time of 6000 hr was considered appropriate, that is twenty four times the required MTBF.

The concept was to work back from the required MTBF and calculate the reliability levels that should be observed early in development for various growth rates. If the first radars were poor initially then deficiencies would have to be detected fairly quickly if a high growth rate was to be attained. A cumulative MTBF of 125 hr over 6000 hr of test with $\alpha = 0.5$, involving 48 failures, would give the same attained MTBF of 250 hr as an equipment having only 34 failures with $\alpha = 0.3$ and an initial MTBF approximately three times as good, ie 50 hr as opposed to 16 hr MTBF. A high α does not necessarily indicate a good design effort as is often thought; it may reflect difficult design problems imposed by a stringent performance requirement, or a poor effort on a straightforward design. However it does show a very thorough effort to discover the causes of failure and eliminate them. It is worth noting that in the limiting case α could well approach zero with excellent design and manufacture, and everything would be right first time! Just random failures and a constant hazard rate! On this project, the technical difficulties were considerable, and an α of between 0.4 and 0.5 was anticipated.

Decisions about the number of equipments depend at present mainly on cost, the available calendar time and the exponential law for appearance of systematic weaknesses. Other factors are the target MTBF and the growth rate anticipated. As a general guide from our experience to date, no single equipment has exceeded 3000 hr of operation following burn-in, and 2500 hr per annum per equipment is a typical maximum rate for accumulating operating hours. The possibility of exchanging an equipment from the reliability test programme after 1000-1500 hr with another equipment allotted elsewhere initially should be considered, because new types of weakness are likely to be found.

No. of Equipments	Factors	Target MTBD - Hours						
		30	50	100	200	300	400	500
1	t p £K	24.0 0.35 398	24.0 0.47 274	24.0 0.62 178	24.0 0.74 131	24.0 0.79 115	24.0 0.82 107	24.0 0.83 102
2	t p £K	24.0 0.42 679	24.0 0.56 461	24.0 0.76 297	24.0 0.94 215	23.3 1.0 185	21.3 1.0 164	20.1 1.0 152
3	t p £K	24.0 0.51 938	24.0 0.67 633	24.0 0.91 405	19.3 1.0 268	16.2 1.0 217	14.7 1.0 193	13.8 1.0 178
6	t p £K	24.0 0.67 1664	24.0 0.88 1115	17.2 1.0 647	11.1 1.0 409	9.1 1.0 334	8.1 1.0 297	7.5 1.0 275

£K = test programme cost
t = test programme time - months. Maximum 24
p = proportion of target MTBD attained
α = Duane growth rate = 0.4
Initial MTBD = 15% of target.

TABLE 2 Example of RGP Costs Analysis

In seeking to minimise total life costs a computer programme is being developed that will readily provide comparisons of the cost effectiveness of various options for a reliability growth programme (RGP) during the development phase. The Duane Model has been adopted for estimating growth. There are fifteen input parameters to the computer programme, including growth rate α, initial MTBD (Mean time between defects), test duration, number of development equipments, number of engineers deployed, down time for defects, cost of hardware, cost of environmental facilities etc. Printouts can be readily obtained showing the effect of changing the parameters.

Table 2 shows an example where α remains constant at 0.4, initial MTBD remains unchanged at 15% of the target and time is limited to two years. Target MTBD and the number of development models are varied, and solutions are computed for the MTBD that should be achieved, with programme time and cost. It can be seen that costs increase with lower MTBD targets - at first sight perhaps an anomaly - but a lower target reflects a more complex equipment with a larger component population which will tend to be more expensive; also more defects are likely to occur which will require more effort on investigations, repairs and modifications. It will take longer to accumulate a specified number of operating hours and all this will add to programme costs. Increasing the number of models for a given target MTBD also increases programme costs, but a higher reliability standard and/or a shorter programme time should be realised. In this example the entire cost of equipments has been charged to the programme, but if they can be utilised elsewhere afterwards, some useful reductions can be accounted. The cost estimates for the RGP have to be carefully considered against the potential savings for the Service life of the total aircraft fleet.

Fig 10 shows the effect on RGP costs in order to attain a given target when α and initial MTBD are varied. The importance of a good design effort in order to achieve a better initial reliability is clearly evident. The higher the "growth rate" α, the lower the RGP costs as would be expected. The percentage initial MTBD and α are not entirely independent, a low percentage initial MTBD will tend to be associated with a high α and vice versa. The more complex the equipment, the higher the proportional increase in costs for a given percentage initial MTBD in order to attain the target. This work on cost estimates is at an early stage, and we hope to improve the computer programme as more data on RGP's is obtained. It is a part of a serious attempt to minimize total life costs attributable to avionics.

Let us return again to the question about the number of equipments for the RGP. If more equipments are tested, then more weaknesses are likely to be found and some will be observed more quickly because each equipment will be slightly different. Also investigations will be helped by availability of other equipments for comparison purposes and for experimental interchange of assemblies. The extent of the improvement in reliability can be inferred from the Duane Model; if n equipments are used and accumulate nt operating hours then, subject to α and k remaining constant, the attained MTBF should then be n^{α} times that for one equipment operating for only t hr - From Appendix Eq. (3) - eg five equipments each operating for 2000 hr with $\alpha = 0.3$ should achieve an improvement factor of $5^{0.3} = 1.62$ over the MTBF for one equipment after 2000 hr.

An important point is that each equipment should be operated for at least 1000 hr, assuming a fairly severe test environment. This is because of the exponential law for the rate of appearance of types of systematic weakness. For example if this condition was not met and five equipments were used to aggregate 2000 hr of operation, each would only show 63% of its weaknesses - ie for a time constant of 400 hr. Even allowing for some variation between equipments it is unlikely that the total number of types of weaknesses would exceed that if only one equipment had been operated for 2000 hr, which would be approximately 9[illegible]% of those in that single equipment. The corresponding figure for 1000 hr is 92%.

Reliability growth modelling must not be regarded as a panacea for evolving reliable equipment. The quality of design must always be the prime consideration.

CONFIDENCE BOUNDS FOR DUANE ESTIMATES

The Duane Model gives the "instantaneous" or attained failure rate, but this is a point estimate on an undefined distribution, and questions are understandably asked about upper and lower confidence bounds. Dr L H Crow has shown[7] that the Duane Model and the Weibull repairable system failure rate model are the same, and has defined a method for calculating the required confidence bounds.

Against our limited experience, we have been a little hesitant about the best solution to this problem. A simple method that has been used is to assume a hypothetical number of failures given by:-

$$\frac{\text{Cumulative test hours}}{\text{Instantaneous MTBF}}$$

This number is entered into the usual Epstein χ^2 formulae for confidence limits, time terminated test, exponential distribution - see Appendix Eq (7). Time is cumulative test hours. It can be claimed that the method is consistent with the Duane concept in that, if no further modifications are introduced, the equipment should exhibit the instantaneous MTBF during further test.

Whichever way the calculation is tackled, there is still the problem of how to adjust the answers in order to allow for the different conditions of use when the equipment is deployed in service. That is the information required by the customer. Some evidence about what happens following development will now be considered.

RELIABILITY GROWTH AFTER THE DEVELOPMENT PHASE

It is fairly common experience that there are always teething troubles when a new equipment is introduced into service, whether it is electronics or motor cars or washing machines! With avionics, it takes about 18 months from first introduction before the reliability standard is reported that was

achieved on late development models. The reasons include a learning phase with the new production line and a learning phase for personnel handling the new equipment. In other words, more reliability growth!

Fig 11 shows an example of such data for another avionic equipment installed on the British Harrier vertical take-off aircraft and operated by the US Marines. This data has been very carefully compiled and all failures have been investigated by the British manufacturer. The initial reliability reported was not as good as expected, but it has now improved to the point that it is much better than the original prediction. A few modifications since introduction into service have contributed to the improvement. The slope is 0.408, calculated by a computer programme that produces an equation for the best fit straight line using the method of least squares, with progressively reduced weighting for the earlier plots.

Experience and logic support the concept that electronic reliability should continue to improve with time, providing transient overstress damage is avoided. When a component fails without any apparent reason, it will often be one which was slightly inferior initially, but good enough to survive even severe burn-in conditions. There will be a very high probability that the replacement will be good, and so the equipment hazard rate will have decreased.

THE PREDICTION PROBLEM

The difficulties in making a numbers count type of prediction at the start of a project with any marked degree of confidence are probably greater today than ever before. So many factors, including those listed in Table 1, can have a profound effect on eventual reliability in service. Extraordinary low failure rates are quoted for many types of component, yet slight lapses in the quality control of a particular batch could result in a vastly higher failure rate if the substandard parts are not detected. But the main emphasis is almost invariably on performance and, despite uncertainties about reliability estimates, development commences. Attempts are always made to predict reliability using what is judged to be the best source data.

In reliability growth programme planning, there is a similar problem of trying to predict the initial MTBF that will be exhibited by the first development hardware. It will be necessary to attempt to make allowances for the technical difficulty and the capability of the design team. Dr Blanks of Australia appreciated the problems and he asked the question[8]; "What value of MTBF during the MTBF-growth phase, which can extend well into the equipment operating (field use) phase, is the reliability prediction process supposed to predict?"

The thought is beginning to emerge that estimates based on reliability growth modelling, once some operating experience has been accumulated, may be more acceptable than the traditional prediction. The MIL-HDBK-217B type of failure rate data will still have a useful role to play in disciplining the checks by designers that components should always be operating at conservative electrical and thermal stress levels. It is also the only basis at present for attempting to quantify logistics for spares holdings, and for apportioning reliability targets to sub-systems.

FUTURE AVIONICS RELIABILITY

Looking to the future, with a further increase in the use of microelectronics, it is envisaged that the factors of quality control in manufacture and of burn-in will become more and more important. Given a perfect design, delivered equipment could be quite unacceptable if these factors are not afforded the right emphasis.

The quality of design is most important and should improve as computers are used increasingly as an aid to design. The more that processes can be automated to reduce the possibility of human error, the better the prospect of achieving high reliability. That is what microelectronics offer. Circuit redundancy techniques are likely to be used more widely.

There are grounds for believing that the overwhelming majority of modern components are potentially failure-free for the service life envisaged. Most failures only occur because of poor quality or overstress. Reliability of future avionics will still depend on the degree to which environmental conditions at the installation can be alleviated, and on the prevention of damage through human error or transient electrical overstress.

There will remain a continuing need to carry out extensive environmental testing of prototype equipment in order to obtain confidence that it will meet reliability requirements. It seems probable that reliability growth modelling will become the accepted method for assessing progress.

CONCLUSIONS

1 Reliability growth modelling is a valuable technique for management in project planning, and for monitoring progress during the development phase.

2 Reliability growth modelling has proved very useful for avionics, and with slight reservations the Duane Model appears to be valid.

3 The slight reservations about the Duane Model are for the early time period, and for the very long time period.

4 The rate of appearance of types of systematic failure follows an exponential law.

5 More attention must be given in modelling to the variation of reliability with different environmental stress levels.

6 Some useful progress has been made with a computer programme for costing reliability growth programmes.

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ACKNOWLEDGEMENTS

The author wishes to acknowledge especially the contributions by Mr P.H. Mead of Ferranti Ltd to the subject of Reliability Growth Modelling.

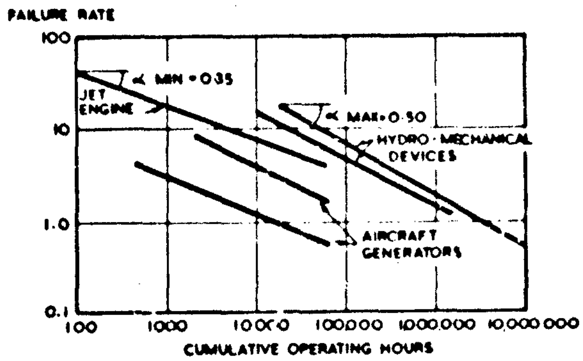


FIG 1

DUANE'S ORIGINAL DATA

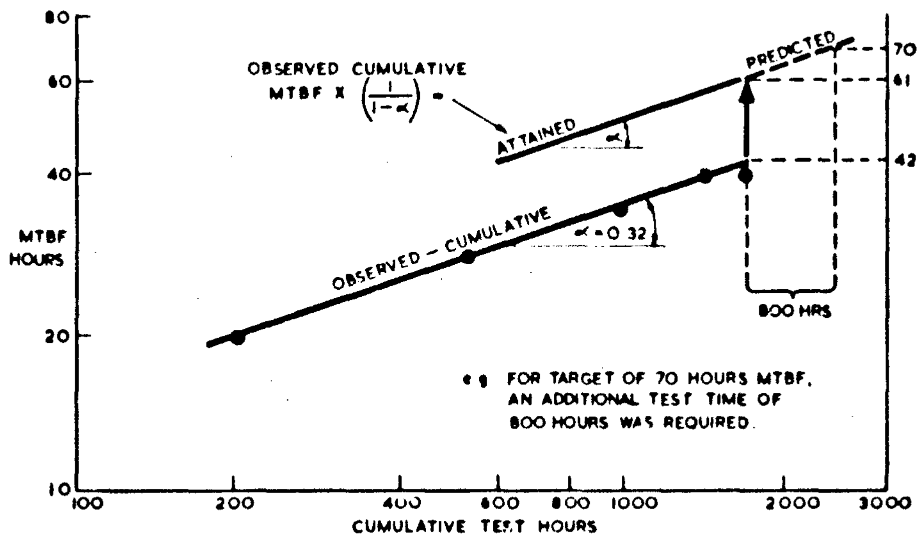


FIG. 2

DUANE CHART FOR RELIABILITY GROWTH OF AN AIRBORNE RADAR

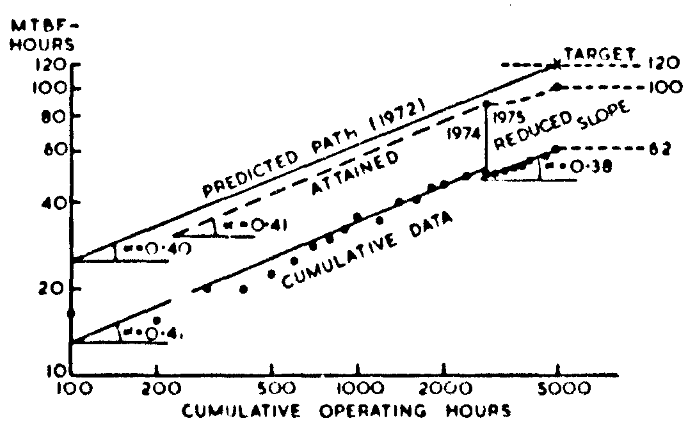


FIG 3

DUANE RELIABILITY GROWTH CHART FOR CURRENT AVIONIC DEVELOPMENT

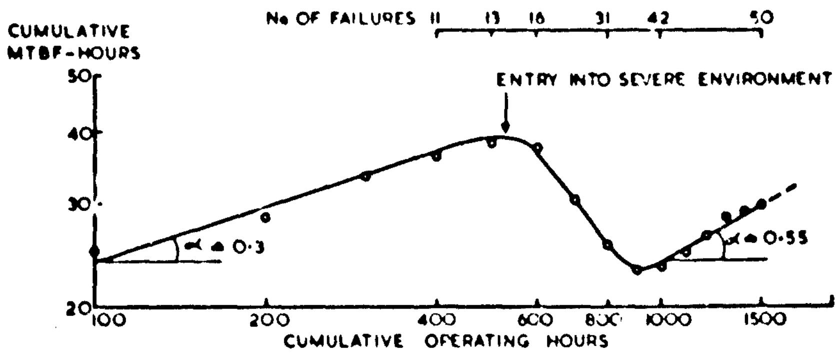


FIG 4

INFLUENCE OF ENVIRONMENTAL FACTOR

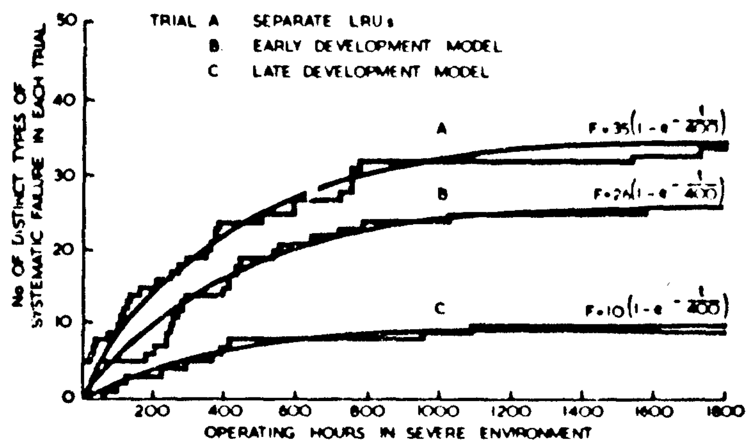


FIG. 5

EXPONENTIAL LAW FOR SYSTEMATIC FAILURES

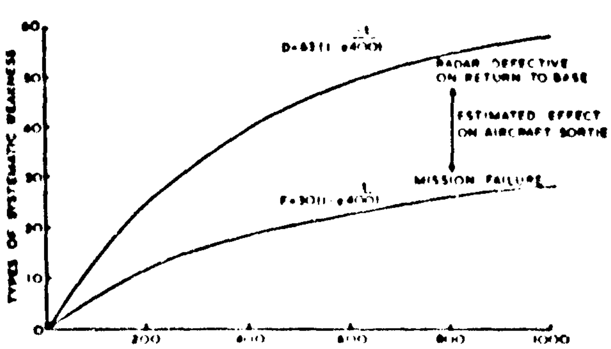


FIG 6

APPEARANCE AND CLASSIFICATION OF SYSTEMATIC WEAKNESSES

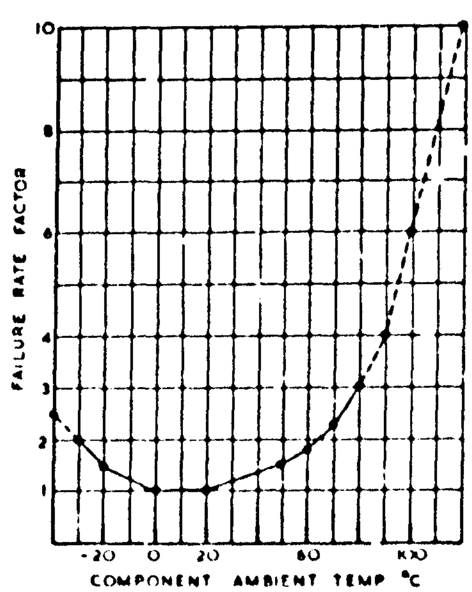


FIG 7

EQUIPMENT RELIABILITY vs TEMPERATURE

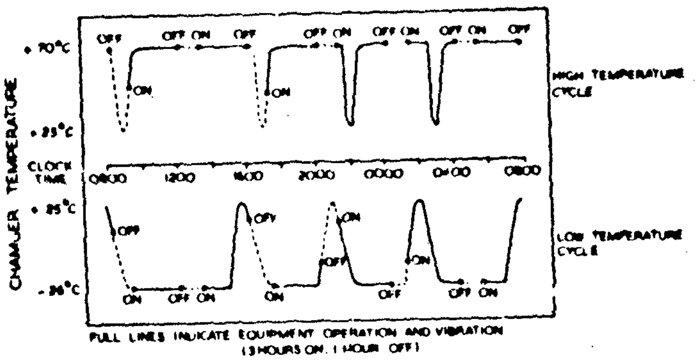
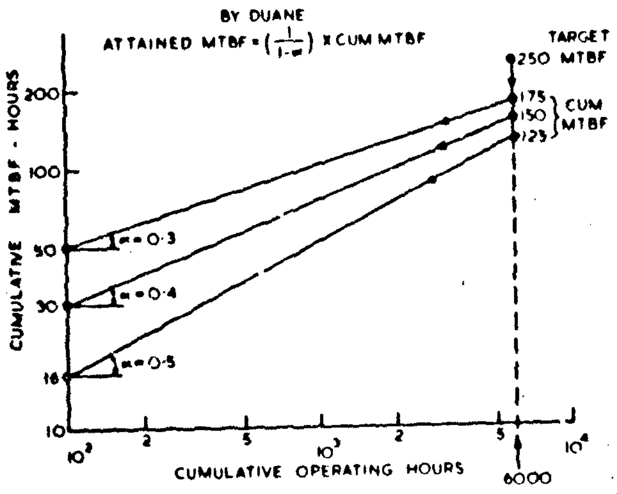


FIG 8
NOVEL ENVIRONMENTAL TEST CYCLES



No OF FAILURES ANTICIPATED IN OPERATING PERIODS

PERIOD HOURS	α		
	0·3	0·4	0·5
0 - 100	2	3	6
100-500	4	6	8
500-1000	4	5	6
1000-2000	6	7	8
2000-4000	10	11	12
4000-6000	8	8	8
0-6000	34	40	48

FIG 9
PROGRAMME PLANNING USING DUANE MODEL

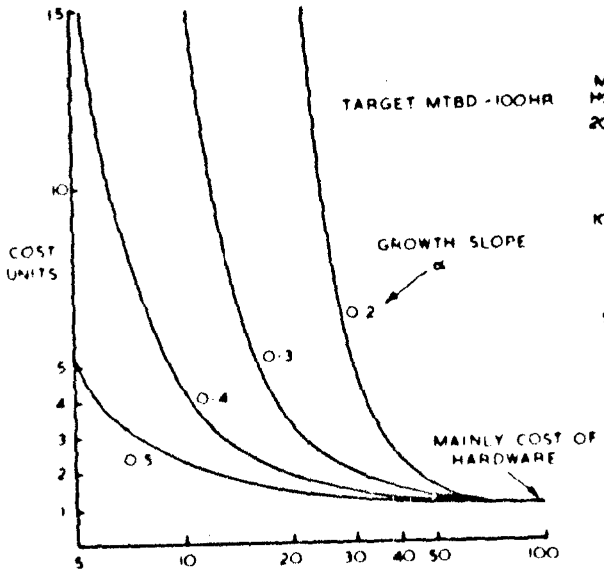


FIG 10
PROGRAMME COST VARIATION

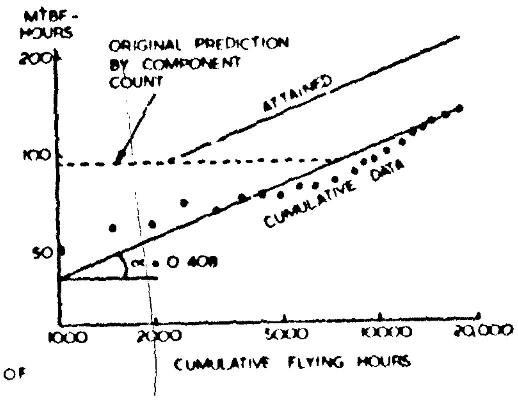


FIG 11
RELIABILITY GROWTH IN SERVICE

APPENDIX 1

THE DUANE MODEL

J.T. Duane of the General Electric Company discovered an empirical relationship between failure rate and testing time for programmes where a continuous effort was maintained to improve reliability by introduction of modifications following experience of failure. The discovery was first reported in an internal GEC paper in 1962.[1]

The mathematical form of the Duane Model is given by the expression:-

$$\lambda_\Sigma = kt^{-\alpha} \qquad (1)$$

Where λ_Σ = cumulative failure rate at time t.

k = constant

t = total operating time

α = a measure of reliability growth, commonly called "growth rate".

In calculating cumulative failure rate, all failures are counted.

If cumulative failure rate is plotted against total operating time on log-log paper, the plots should lie on a straight line having slope $(-\alpha)$.

The instantaneous attained failure rate at time t will be lower than the cumulative failure rate because improvements have been introduced.

(1) can be written as

$$\lambda_\Sigma = \frac{F}{t} = kt^{-\alpha}$$

where F = total failures observed in time t

$$\therefore F = kt^{1-\alpha} \qquad (2)$$

The instantaneous failure rate is obtained by differentiation

$$\text{Hence } \lambda_i = (1-\alpha)kt^{-\alpha} \qquad (3)$$

It follows that plots of instantaneous failure rate against test time on log-log paper will also lie on a straight line having slope $(-\alpha)$. This line will be parallel to the line through plots for cumulative failure rate.

$$\text{Combining (1) and (3) gives } \lambda_i = (1-\alpha)\lambda_\Sigma \qquad (4)$$

Since MTBF can be considered as the inverse of failure rate, equation (4) can be changed to read

$$\theta_i = \frac{\theta_\Sigma}{1-\alpha} \qquad (5)$$

where θ_i = instantaneous attained MTBF

θ_Σ = cumulative MTBF

Equation (5) provides a simple mathematical model by which management can quantify progress.

The rate of change of MTBF is obtained by further differentiation.

$$\text{From (1) and (5) } \theta_i = \frac{t^\alpha}{k(1-\alpha)}$$

$$\therefore \frac{d\theta_i}{dt} = \frac{\alpha t^{\alpha-1}}{k(1-\alpha)} \qquad (6)$$

Epstein[2] developed the following formula for the single sided lower MTBF Confidence Limit θ_L, assuming an exponential distribution.

$$\theta_L = \frac{2nT}{\chi^2\ (a, 2r+2)} \qquad (7)$$

where n = number of equipments on test

T = test time for each equipment, same for each

a = 1 - Confidence Coefficient

r = total number of failures

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2 Epstein B. Statistical Techniques in Life Testing PB171580, US Department of Commerce.

ILLUSORY RELIABILITY GROWTH

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SUMMARY

The present meaning of Reliability Growth is identified and contrasted to earlier concepts. Present need to devise effective means for administering the later phase of avionic development is recognized. It is during this development phase that an abundance of system failures caused by shortcomings of design, workmanship, and parts selection, mask more or less completely the inherent reliability achievable upon development completion. The mathematical uncertainty of prognosticating a valid schedule for elimination of all pattern failures and achievement of required reliability on the basis of early test experience is examined. It is concluded that accepted means must be used for quantitative MTBF measurement in the absence of pattern failures, and that quantitative values for MTBF produced by typical growth monitoring in the presence of an abundance of pattern failures can be dangerously misleading.

INTRODUCTION

The term "Reliability Growth" in the last few years has assumed a meaning somewhat different than in earlier years. In the late 1940's when reliability as an engineering specialty first emerged, the failure rate of electronic and avionic systems was generally found to be relatively constant during the useful life of the system, and constant failure rate mathematics (probability and statistics) quite adequately sufficed for reliability problem solving. With the emergence of solid state circuitry, some evidence began to appear here and there to the effect that the failure rate of solid state elements (notably transistors and diodes at the time) sometimes decreased somewhat during the life of the system. This decrease was more a gradual and uniform change over the entire useful life, rather than a rapid decrease during early life and relatively constant failure rate thereafter. The existence of this phenomenon brought forth identification as "reliability growth". The extremely low failure rates of the more successful solid state elements, especially integrated circuits, rapidly led to the development of increasingly complex avionic systems and the establishment of design guidelines for solid state circuitry and digital design considerably different than the customary design approaches of the past. The lure of expanding vistas for electronics and avionics brought large numbers of apprentice designers into the profession. Understandably, the characteristic that frequently brought up the rear of the development procession was reliability. Unfinished developments sometimes were released for production because of overly optimistic development time tables. The frequency of failure in operating hardware that had not been meticulously shepherded through to the proper end of development was intolerably high but could be made to decrease to varying extents in response to development "clean-up". Again, and understandably, the term "reliability growth" now appeared more and more frequently in programs going through the final stages of development after production had already begun. Reliability growth in this application can not imply that any element of the avionic design has a failure rate which will gradually decrease over its useful life. Rather, the implication is to unfinished development, suffering from an unnecessarily high failure rate because of design error, workmanship insufficiency, and/or poor parts selection. The improvement in failure rate can only come about because of significant effort on the part of development personnel to rectify these shortcomings. The significance of identification of such so-called reliability growth is that it is difficult to ascertain before hand as to just how much the failure rate can be reduced with effort limited to practical bounds. This paper is then chiefly concerned with reliability growth and present approaches to its control when considered in respect to failure rate reduction by specific effort in the areas of design, workmanship, and parts selection.

HISTORICAL BACKGROUND

In the early days of reliability, equipment and systems for which high reliability was important received very close development scrutiny. Laboratory procedures fostered the emergence and identification of failure mechanisms. Those judged to be likely frequent repeaters were eliminated through design, workmanship, and parts selection efforts. With some patience, a system would reach the point where the last hundred or so failures would include no two like failure mechanisms. This resulting heterogeniety of failure mechanism guaranteed that the exponential distribution would accurately describe the probability of future failure, and it yielded constant failure rate reliability. For a system which had reached a condition of unrepeating (even though frequent) failures, it was found that further permanent elimination of failure mechanisms did not produce measurable reliability improvement in near future operation. If reliability was still too low (unrepeating failures too frequent), major redesign often involving basic change of design approach was judged essential.

With constant failure rate equipment and systems, techniques for reliability (MTBF) measurement were developed and improved to permit maximum confidence in minimum test time[1]. Such measurement via test is well known. It is important that most such procedures insist that if pattern failures (repeating failure mechanisms) appear, the test is invalidated. In other words, the test is valid only so long as heterogeniety of failure

Today, in the presence of high complexity, solid state, digital avionic design, some developers can be found who succeed in permanently eliminating all failure mechanisms of high repetition frequency during their scheduled development, and who then perform a standardized constant failure rate reliability verification test and establish the presence of adequate reliability without need for post-test remedy. While such a feat for a development which departs but slightly from a design of long standing and great experience may be judged not especially exceptional, there have been cases of such accomplishment with radically new design. Probably, however, the majority of developments are forced to choose between minimal departure from past adequate design, and extended effort to obtain needed reliability. Unfortunately the need for development business and the large number of would-be customers with limited funds and high reliability demands leads to many perplexing situations.

In the last ten years there has been an ever increasing technical press addressing the aforementioned most recent concept of reliability growth. Some customers are proposing means to hopefully assess reliability very early in the development evolution of functioning hardware, and then to follow the apparent reliability during a protracted testing program in order to measure reliability growth. From such findings it is hoped to be possible to predict further future reliability growth against future schedule and available funds, in order that decision may be made as to ultimate reliability success, and appropriate action taken early if necessary. Thus it would seem vital to scrutinize popular techniques for supposedly measuring reliability growth to determine whether the calculated growth is illusory or real.

The basis for one of the more if not the most popular growth measuring technique is the 1970 reliability approach advocated by General Electric and identified as "Reliability Planning and Management (RPM)"[2]. This technique in turn is based on a 1962 paper by a G.E. employee, Mr. J. T. Duane[3], and further elaborated in 1968 in a paper by E. O. Codier[4], also of G.E. Messrs. Selby and Miller characterize their RPM theory by using the "Duane Plot" to track reliability growth over an extended development test period which typically accumulates ten thousand operating hours of test. They note that reliability at the beginning of the Duane Plot (usually after one hundred hours of test) is typically ten percent of the predicted MTBF, and most often can be expected to rise at a rate proportional to the square root of the accumulated test time. In 1973, G.E. concluded a study which applied the Duane method of growth assessment to several multi-year equipment developments. In the final report[5] it is noted that evidence of reliability growth depends on the distribution of failure mechanisms, the detection of failure mechanisms, and the rate of failure removal. Typically, newly developed equipment exhibiting MTBF at ten percent of the predicted value was found to be constrained by problems equally divided among design, workmanship, and parts. If design, workmanship, and parts were all less deficient initially, then the MTBF would initially be closer to the predicted value. Obviously if failure observations enter growth calculations before very much development clean-up has taken place, failure frequency will decrease as clean-up progresses. However, as G.E. has observed, the distribution of failure mechanisms must include a significant proportion of high failure rate mechanisms (to provide the easy to recognize pattern failures), which are relatively easy to detect (thus receiving specific attention) and quick to permanently eliminate (in order to provide readily recognizable reliability growth). Many case histories confirm that this situation is frequently encountered.

If MTBF calculations must await completion of most of the design and workmanship clean-up, and it is then found that the remaining observable failures do not readily respond to further clean-up effort, and this failure rate is unacceptably high, it is very late in the program to begin the needed basic redesign. There is little question as to the desirability for some means to assess the level and rate of decrease of failure rate at the earliest possible moment in development evolution, provided such assessment can lead to a correct hypothesis concerning the possibility of reaching the required reliability within a critical schedule.

MATHEMATICAL VALIDITY

Probability is the mathematical means for progressing from general laws of physics (nature, etc.,) to specific circumstances when it is desirable to predict the future. Thus if we have the true MTBF, and know that it will remain constant in the intended application, it is possible to calculate the probability of future failure. Statistics, conversely, embrace the mathematical means for progressing from specific observations to general laws, and induction is required. Because of the nature of the universe and our limited knowledge of it, statistics is a much broader field of mathematics than is probability. Hopefully we limit the use of statistics to: 1) the situation where we are unfamiliar with the physical laws that pertain, and/or 2) the situation where the details of all controlling factors are known but so voluminous that a detailed exact calculation is not justified in the presence of available statistical accuracy. In reliability we may be able to mathematically describe sufficiently one or more actual failure mechanisms, but in general we cannot begin to describe any significant quantity of failure mechanisms to permit exact calculation of failure probability. Generally, where enough is known of a particular mechanism, it becomes practical to eliminate it.

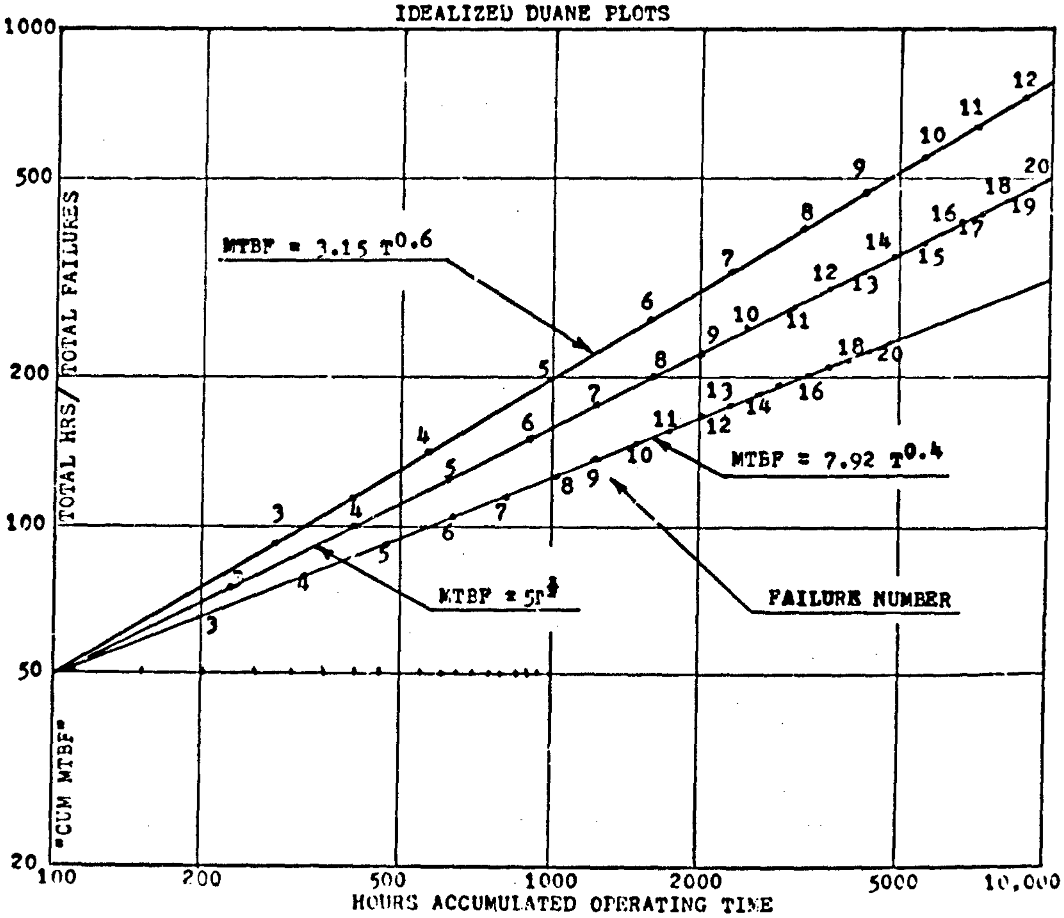
The fact that a heterogeniety of failure mechanisms permits them to be considered with the exponential distribution has more than anything else made it possible to measure MTBF and calculate probability of future failure with useful accuracy. Knowing inclusion of any failure mechanisms whose prevalency upsets this heterogeniety principle, leads to error and gross error in the computation of MTBF based on observed failures. On the other hand, repetitive (pattern) failures are bound to exist to some extent during a development, and such mechanisms must be eliminated. Hence close scrutiny cannot be denied them. Thus the

yet taken place, and MTBF assessment is based on an "if they are eliminated" basis, then the accuracy of MTBF assessment will hinge on adequacy of later elimination, absence of any related design deterioration or introduction of new failure mechanism, and similar considerations.

DUANE PLOT

The Duane Plot, as illustrated herewith, at the time of each failure takes a measurement of the total operating time of the system on test, and divides this time accumulation by the total number of failures observed up to that time. This quotient, as so-called cumulative MTBF, is plotted versus the aforementioned total accumulated time on log-log graph paper. It is customary to recommend that the first plotted point be at one hundred hours time or at the time of the next failure thereafter. For typical equipment the test may be continued if all goes well until as many as ten thousand hours are accumulated, in order to display all the significant reliability growth to be encountered. It is usually expected that the one hundred hour cumulative MTBF will be approximately ten percent of the predicted MTBF, and that the slope of the plot as more and more points are plotted will approximate the one-half power of accumulated time.

IDEALIZED DUANE PLOTS



During the one hundred initial hours of operation consideration can be given to just what rules will govern data collection. Decision must be made as to what time to count and which failures to count. Unnecessary inflation of the failure count will yield low MTBF but more significant positive reliability growth. Austere failure counting may lead to administrative difficulty concerning whether to count certain future failures. Generous decision for time counting makes possible reaching the end of the test (ten thousand hours) by an earlier date but it may raise administrative question as to the adequacy of performance during all counted time. In any case is must be noted that MTBF in the presence of pattern failures cannot be used to calculate system reliability, and thus the MTBF plotted on the Duane graph early in the test period is indicative of growth but not of reliability.

Scrutiny of the above illustration of hypothetical Duane Plots for three different also hypothetical equipments can offer some insight. The upper curve illustrates reliability growth proportional to the 0.6 power of time. Failures number 3 (at 275 hours) through number 12 (at 8800 hours) are plotted as if they occurred at the precise moment to mathematically make the plot follow a straight line. In real life the actual time of each failure occurrence would be far more randomized, and a plot like that illustrated could only be

expected if a large number of equipments were being tested simultaneously, and the plotted point represented the average time of failure occurrence.

The middle curve is for the highly touted growth characteristic where MTBF is proportional to the square root of accumulated test time. The lower curve is for MTBF proportional to the 0.4 power of time. On the horizontal 50-hour calibration line are marked the time of occurrence of successive failures as would be expected if no growth took place (a failure every fifty hours on the average). With the sequence number of each failure identified for each of the four conditions, the illustration makes it possible to see how much the failure rate is spread out or closed up for a given change in slope. In an actual test, the randomized time of occurrence of each failure distinctly separate early in the test permits considerable option on just what slope straight line is judged best fit for the data.

This type of plot can be seen to smooth initial data least and final data most. Initial data reflect MTBF calculations with greatest departure from true MTBF because of the presence of pattern failures in large measure. The randomized time of their occurrence greatly obscures early slope indication. The smoothing effect on final data brought about by the mass of early data still included in each calculation tends to negate the increased value of MTBF evaluation based on data with most of the pattern failures eliminated. The close spacing of failures toward the end of test make the plot quite insensitive as an indicator of change of slope as could be brought about by exhaustion of the supply of pattern failures, with the result that the test is likely to continue for some time unnecessarily after reliability growth has stopped. In summary, the Duane Plot may be more an indicator of skill in establishing optimum rules for data collection and starting the plot to yield a desired slope than an indicator of how much development clean-up is needed, when it is likely to be finished, and whether the then resulting reliability will be sufficient.

Mathematical evaluation of the cumulative log-log plot shows that the instantaneous value of the ordinate (instantaneous reliability) can be calculated by multiplying the plotted cumulative ordinate by $1/(1-a)$ where a is the slope of the best fit straight line through the plotted points. For the middle curve where the slope is ½, the instantaneous reliability (MTBF) is twice the plotted value. However, since the slope is so dependent on early plotting technique and data processing rules, true MTBF should be determined by accepted verification test means rather than by assessment of the Duane Plot.

CONCLUSIONS

The need to devise and employ means for early assessment of reliability during the development cycle is real. The existence of a proliferation of pattern failures is usual. Reliability prediction if properly performed has specific value, and standardized reliability verification tests can be valid for measuring true reliability is properly performed. Monitoring the process of pattern failure elimination can be an administrative necessity in many situations. The basic danger in popular reliability growth control methods is in the assumption of accuracy of MTBF when calculated in the presence of many pattern failures, and in any assumption that reliability growth can be counted upon to follow straight line properties, to have a particular slope (or even a positive slope), and to be predictable for identifying end reliability within a particular schedule.

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EXPERIENCED IN-FLIGHT AVIONICS MALFUNCTIONS

George T. Bird
G. Ronald Herd

SUMMARY

The status of current avionics reliability in the field has been evaluated by a study of 98 types of avionics equipment used in a variety of aircraft during a six-month period in 1970. The MTBFs were analyzed by aircraft type and by equipment category (i.e., communication, radar, flight controls, computers, etc.) to reveal correlations with functional complexity. About 4,000 in-flight malfunctions from one type of aircraft covering 28 different equipment types were investigated to show failure modes, repair actions, and probable design causes.

INTRODUCTION

In order to satisfy demands for increased operational capability in high performance aircraft, avionic systems are necessarily becoming functionally more complex. This growing complexity has led to more reliance on computer techniques for the automation of system operation and control, particularly in special purpose aircraft. Although reliability of systems (given the level of complexity) h improved in recent years, the increased complexity required in new systems may compromise that reliability achievement. The tradeoff between complexity and reliability leads to critical questions for aircraft system project managers and avionics equipment designers undertaking a new development program:

(1) Will the proposed new avionics design satisfy the specified mean-time-between-failures (MTBF) requirement?

(2) In what technical areas (e.g., failure modes) should design effort be emphasized to achieve the specified requirement?

(3) How much development phase design evaluation testing should be expected to actually achieve and demonstrate the specified reliability requirement?

This paper deals with the first two questions and provides a basis for another paper responding to the third.

AIRCRAFT PROBLEM AREAS

The avionics subsystem is involved in more aircraft failures than any other subsystem, as shown in Figure 1. The distribution of "problem areas" within major subsystems in several types of military aircraft (attack, fighter, helicopter, and special purpose transport types) is the result of an analysis of field failure reports for 1.2 million aircraft failures observed during more than a million flight hours. Avionics subsystems experienced one failure in about 2.8 flight hours. Because of differences in avionics complexity and other factors, the proportion of avionics failures to total failures ranged from 27% in helicopters to 52% in supersonic fighters.

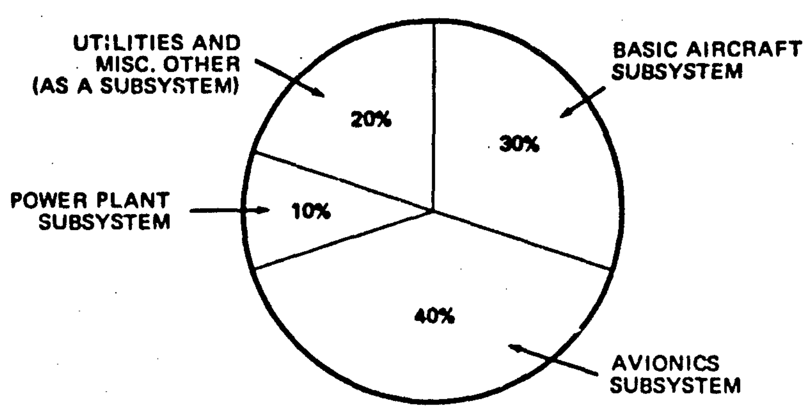

Figure 1. Aircraft Problem Classification, All Aircraft Types Combined

Some of the avionics equipments observed were procured under contracts that included a reliability specification (R-Spec) as part of the overall design specifications. The observed MTBFs for those avionics equipments purchased under R-Spec conditions are plotted for each aircraft type in Figure 2 against complexity, for comparison with average past MTBF experience represented by MIL-STD-756 predictions (θ_p). Overall, the mix of installed R-Spec avionics equipments across all types of aircraft shows MTBFs higher by a factor of better than two-to-one than would have been predicted by MIL-STD-756, based on equipment failures reported in approximately 285,000 flight hours.

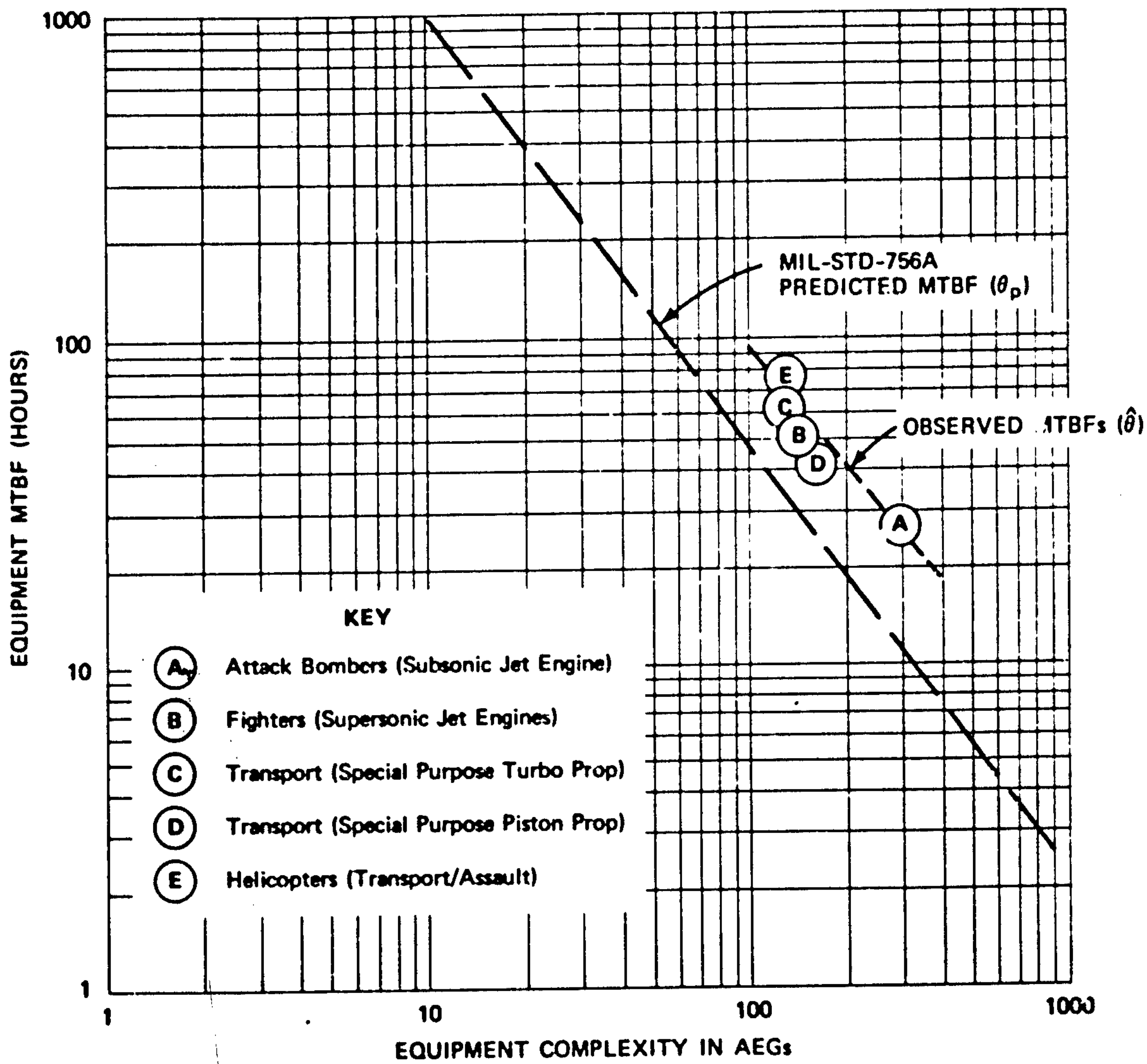

Figure 2. Observed Avionics MTBFs of "R-Specified" Equipment Installed on Various Aircraft Types

A direct comparison between R-Spec avionics equipment and equipment without contractual reliability requirements (Un-Spec) is presented in Table 1, by aircraft type. The last column of this table gives the ratio between specified and unspecified MTBFs for each type of aircraft. One should note that complexity of the typical equipments is not the same for each, and an adjustment for complexity is made in the later analyses.

Table 1. Avionics MTBF in Military Aircraft

Aircraft General Category	No. Avionic Equipt (n)	Total AEG (N)	A Typical Equipment in the Avionics System				
			AEG (Avg N/n)	θ_p (hrs)	$\hat{\theta}$ (hrs)	$\hat{\theta}/\theta_p$	$\hat{\theta}_s/\hat{\theta}_u$
(A) Subsonic Jets (Attack - 3 Basic Types)							
R-Spec	19	4709	300	10.5	27	2.56	
Un-Spec	5	487	97	46	70	1.54	
Total	24	6196	258	12.5	31	2.47	1.67
(B) Supersonic Jets (Fighter - 3 Basic Types)							
R-Spec	7	1000	143	28	40	1.43	
Un-Spec	8	2546	318	9.1	36	3.92	
Total	15	3546	236	13.3	38	2.82	0.37
(C) Turbo Props (Transport - 2 Basic Types)							
R-Spec	9	1192	132	31	52	1.65	
Un-Spec	31	5617	181	20	35	1.76	
Total	40	6809	170	21	37	1.74	0.94
(D) Piston Props (Transport - 1 Basic Type)							
R-Spec	8	1144	143	30	39	1.34	
Un-Spec	8	997	125	33	34	1.03	
Total	16	2141	133	31	37	1.17	1.30
(E) Helicopters (Assault - 3 Basic Types)							
R-Spec	6	800	133	38	62	1.61	
Un-Spec	13	1681	129	33	35	1.07	
Total	19	2481	131	34	40	1.18	1.51

CURRENT RELIABILITY STATUS OF AVIONICS

A total of 98 different avionics equipment types (predominantly analog-function) in 9 basic functional categories were involved in the analyses shown in Figures 1 and 2. Only 35 of the 98 types had been developed under contractually specified MTBF requirements. A 130% improvement (2.3-to-1) in analog-function avionics equipment reliability (MTBF) appears to have been achieved, on the average, in avionics equipment developed under specified requirements. Those developed without specified requirements achieved MTBFs approximately 60% higher than predicted by MIL-STD-756. A graphical comparison between the achieved reliability and the avionics reliability prediction curve of MIL-STD-756 is shown in Figure 3, based on numerical data presented in Table 2.

The MIL-STD-756 prediction procedure was developed in the late 1950s on the basis of data compiled from in-flight experience on predecessor avionics equipments of similar functions. The predecessor equipments were operational in 1958, and the current data apply to equipment operational in 1970. Thus, the 2.3-to-1 MTBF improvement in R-Spec avionics equipment was achieved in 1.2 generations (i.e., 10 years per generation) of equipment design/development during a period when reliability was receiving considerable attention but had not been uniformly converted into design specifications. Overall, a reliability requirement contractually specified resulted in MTBF 45% higher than that achieved by systems without specified requirements.

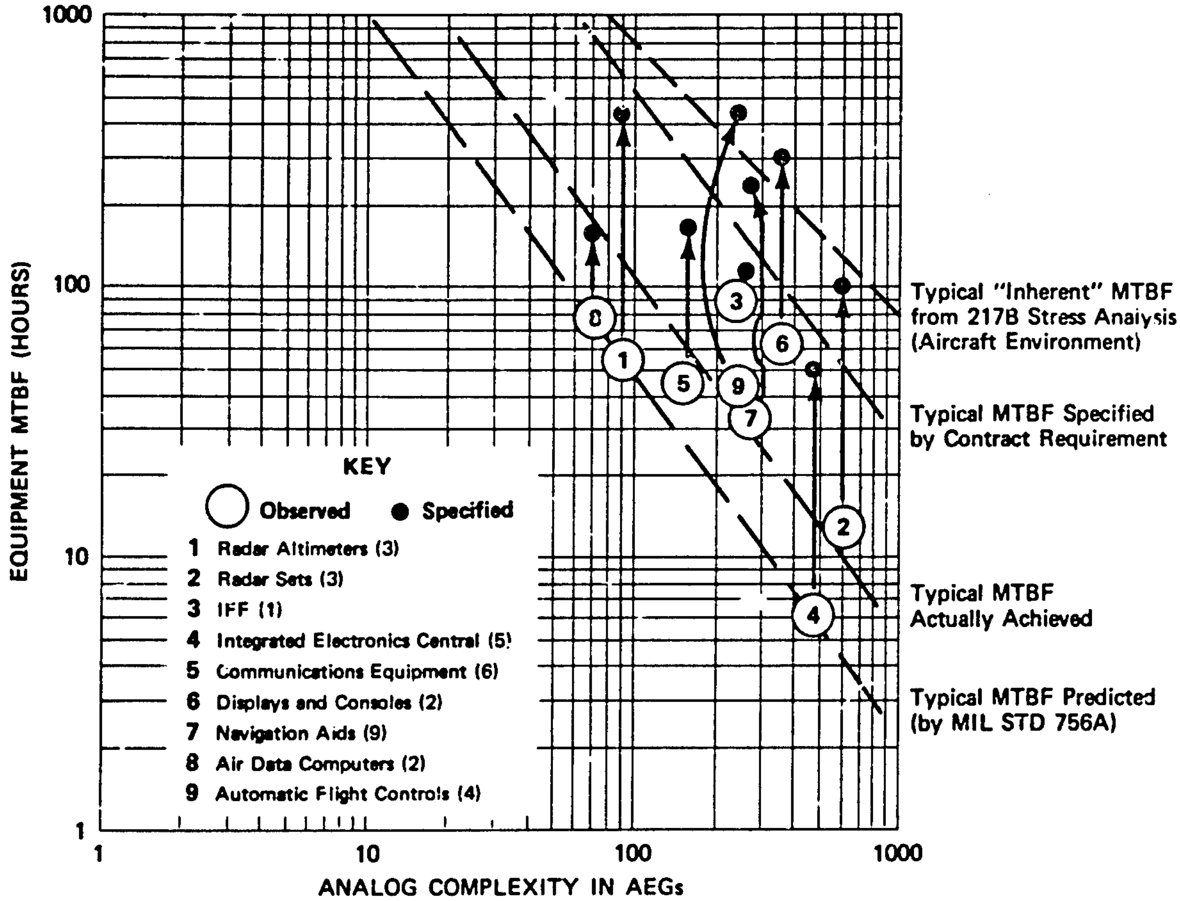

Figure 3. Typical MTBF for 9 Basic Equipment Categories, Based on 35 Avionics Equipments With Contractually Specified Reliability Requirements

The scattergrams of average MTBFs and functional complexity (in AEGs*) for the 35 avionics equipments (within the 9 categories) show both "observed" achieved MTBFs and their corresponding specified MTBFs. Specified MTBF requirements, on the average, generally fall between the upper "inherent" MTBF boundary predicted by MIL-HDBK 217 part/stress analysis (for aircraft "inhabited" environmental conditions), and the lower MTBF boundary predicted by MIL-STD-756 AEG analysis (for aircraft "uncontrolled" environmental conditions). It can be deduced from the scattergram that the relative complexity of the equipment was not always considered in specifying the particular value of MTBF. However, using the average "specified" MTBF line in Figure 3, it would appear that a 10-to-1 improvement over previous MTBFs (as predicted from MIL-STD-756) had been desired.

* An active element group (AEG) is defined as a circuit function comprising one active element (transistor, electron tube, integrated circuit, relay, etc.) and its associated passive elements (resistor, capacitor, inductor, connector, etc.), as defined in MIL-STD-756A.

Table 2. Avionics MTBF/Complexity Analysis*

Item	① Radar Altimeters	② Radar Sets	③ IFF	④ Integrated Electronic Central	⑤ Communication Sets	⑥ Displays and Consoles	⑦ Navigation Aids and Computers	⑧ Air Data Computers	⑨ Automatic Flight Controls	Combined Groups
<u>R-Specified</u>										
No. Equip (n)	3	3	1	5	6	2	9	2	4	35
Avg AEGs (N)	85	590	225	445	140	325	270	70	240	270
Spec. MTBF (θ_0)	450	100	125	50	167	300	247	167	430	145
Predicted (θ_p)	59	4.7	18	6.8	32	10.5	11	83	15	
Observed ($\hat{\theta}_s$)	54	13	91	6.2	44	62	33	83	42	
$\hat{\theta}_s / \theta_p$	0.9	2.8	5.1	[illegible]	1.4	6.[illegible]	2.9	1.0	2.9	2.3
$\hat{\theta}_s / \theta_0$ (%)	12%	13%	14%	12%	26%	21%	13%	50%	10%	17%
θ_0 / θ_p	8	21	7	7	5	27	22	2	29	15
<u>Unspecified</u>										
No. Equip (n)	4	6	2	2	12	15	8	7	7	63
Avg AEGs (N)	105	410	80	560	140	145	275	50	210	190
Predicted (θ_p)	42	7	63	5	31	30	11	111	18	
Observed ($\hat{\theta}_u$)	27	18	74	8	50	38	31	66	26	
$\hat{\theta}_u / \theta_p$	0.6	2.5	1.2	1.6	1.8	1.4	2.8	0.6	1.4	1.6
$\hat{\theta}_s / \hat{\theta}_u$	1.4	1.1	4.2	0.6	0.8	4.4	1.0	1.7	2.0	1.4
<u>Combined</u>										
No. Equip (n)	7	9	3	7	18	17	17	9	11	98
Avg AEGs (N)	95	465	130	480	140	170	275	55	220	220
Predicted (θ_p)	48	6	34	6	29	2[illegible]	11	103	17	
Observed ($\hat{\theta}_{su}$)	34	16	78	7	48	2[illegible]	32	70	30	2.58
$\hat{\theta}_{su} / \theta_p$	0.7	2.6	2.3	1.1	1.6	1.7	2.9	0.7	1.8	1.8

Values of $\hat{\theta}_s / \hat{\theta}_u < 1.0$ may be due to one or more reasons:

- Differences in functional performance requirements not adequately reflected in the prediction methods of MIL-STD-756A.
- Differences in equipment in-flight operating duty cycle (not reported from the field and hence not compensated for in the data analysis).
- MTBF requirements contractually specified too late in the acquisition program to have any significant influence on design.

This study reveals that MTBF achievements to date are still far short of specified requirements -- i.e., less than 25% of the specified MTBF was actually achieved in the field. To illustrate, assume that a new item of avionics equipment is to be procured to satisfy a specified MTBF = 200 hours. Assume the design will require approximately 200 AEGs to perform specified functions. From Figure 3, it can be determined that this item will achieve an in-flight MTBF of approximately 45 hours, based on current average experience. Thus, our experience indicates that the item will be designed, developed, manufactured, and delivered to the customer, where its observed MTBF under service-use (operation and maintenance) conditions will be 45 hours -- i.e., less than 25% of the specified 200-hour contract requirement.

Achievement of specified MTBFs corresponding to the average specified MTBF line in Figure 3 is feasible if sufficient design evaluation testing is performed during the design/development phase to identify the failure modes and correct the underlying failure causes. This must include enough environmental testing under simulated aircraft installation to verify adequacy of each corrective action to prevent or minimize recurrence of these failure modes.

CLASSIFICATION OF EQUIPMENT FAILURE

A study was performed on the avionics equipment for a single type of aircraft. The vehicle for this detailed investigation was a turbo-prop special service type aircraft because it carried the first large avionics subsystem (28 different AN/ equipments), including an integrated electronics central computer for system operation and checkout. Operation of much of the installed avionics equipment was controlled and monitored by a central computer. A very important part of the system was the software (computer programs) by means of which data from various system elements were coordinated and controlled for performance of subsystem functions. In addition to the operational program, there were several test and diagnostic programs which perform system and equipment tests and provide trouble diagnosis for maintenance and repair purposes.

In general, failure modes (except software failures in one item) did not vary appreciably among the 28 avionics equipment types studied. Results of the failure analysis are presented in Table 3, using the following definitions

(1) Hardware Failures

- Electronic -- degraded or incorrect performance, intermittent performance, no outputs, shorts, opens, fluctuating or unstable performance characteristics, failure to transfer (i.e., switch) to redundant element, etc.
- Mechanical -- broken, jammed, bent, loose, binding, or damaged mechanical parts, fasteners, bolts, electrical contact/connectors, support frames, panels, sockets, etc.
- Environment -- exposure to excessive vibration, temperature, humidity, or other ambient conditions which could have induced the observed failure.
- Other -- failures due primarily to defective or burned out light bulbs in indicator lamps and panel lamps, and blown fuses or defective circuit breakers.
- Unknown -- observed and verifiable equipment functional failures (e.g., failure to operate) not traceable to specific failure cause, removed and replaced (or adjusted) to return the equipment to operational status.

(2) Software Failures Malfunctions traceable to faulty input parameters or conditions due to wrong logic program for computers or faulty tape or card for program or checkout.

(3) Anomalies Operating in-flight malfunctions or failures to pass diagnostic automatic test criteria which could not be verified in maintenance checkout, these are classified "No Defect" and returned to service without repair.

Table 3. Number of Equipment Failures by Failure Classification and Repair Actions in 28 Types of Avionics Equipment

Failure Classification	Equipment Failures		Repair Actions in Percentage of Failure Cases	
	Number Reported	Percent of Total	Replace/ Repair	Adjust/ Alignment
(1) Hardware Failures				
Electronic	760	19%	59%	41%
Mechanical	429	10	33	67
Environment (Induced)	103	3	25	75
Other (Lamps, Fuses)	452	11	18	82
Failure Cause Unknown	1068	26	66	34
All Hardware Failures	2812	69%	50%	50%
(2) Software Failures	*84	2%	15%	85%
(3) Anomalies	1179	29%	<1%	99+%
Total	4075	100%	35%	65%

* Except for one avionics central computer wherein 17% of total failures were due to software failures.

As indicated in Table 3, 45% of all malfunctions were traceable to specific hardware and software causes. Unidentified hardware problems (26%) and anomalies (29%) combined produced 55% of all reported malfunctions, these two failure classifications represent all the "mysterious" unidentified interactions, interface tolerance incompatibilities, and interference problems.

About 65% of all malfunctions were corrected by alignment or adjustment (A&A) actions not involving repair or replacement (R&R) of hardware or software elements. The ratio of A&A to R&R corrective actions serves as another indicator of interface tolerance and instability problems not identified, since about 50% of these A&A corrective actions were spent in chasing the anomalies described above.

For immature designs, the anomalies usually contribute about one-third of all failures, and this pattern has been consistent over the years among all types of electronic equipments in all kinds of environments and/or functional applications.

3. FAILURE MODE ANALYSIS IN TYPICAL AVIONICS EQUIPMENTS

For design correction of specific failure modes observed in avionics equipment (during flight or test), it is necessary to first identify the failure problems having significant impact on reliability and then determine the failure causes underlying the observed failure modes.

(1) Comparison Between Observed Failure Rates and Predicted Values

For example, beginning with the lower level of configuration (e.g., unit, component, or part), observed failure rates in critical failure modes are computed and compared with predicted failure rates for the same elements. For the purpose of illustration, consider a typical avionics equipment which had experienced 48 failures in 2,000 flight hours. As shown in column (3) of Table 4, the observed failure rate was divided among 26 units making up the equipment. The predicted failure rate for each unit, shown in column (4), is based on reliability stress analysis performed in accordance with MIL-HDBK-217, and thus represents the theoretical "inherent" failure rate of each unit attributable to parts and components making up the unit. The ratio of observed failure rate to predicted failure rate, k, is recorded in column (5); this ratio indicates the degree of improvement potential by correction of design problems associated with individual units.

Table 4. Observed and Predicted Failure Rates in a Typical Avionics Equipment

Unit Identification	Observed		Predicted Failure Rate (Failures Per 10^6 Hrs)	Failure Rate Ratio
	Number of Failures	Failure Rate (Failures Per 10^6 Hrs)		$k = \frac{\text{Observed}}{\text{Predicted}}$
(1)	(2)	(3)	(4)	(5)
100	1	500	80	6.3
200	3	1500	3200	0.5
300	0	0	300	0
400	13	6500	200	32.5
500	0	0	500	0
2200	6	3000	100	30.0
2300	2	1000	1000	1.0
2400	1	500	1000	0.5
2500	8	4000	400	10.0
2600	5	2500	1200	2.1

(2) Identifying Major Problem Areas for Engineering Investigation

Failure rate ratios (k values) are plotted by relative order of magnitude, as illustrated in Figure 4. The "expected" range of k values in this example extends from ratios of less than one to ratios of between three and four, with an average ratio, $\bar{k} \approx 1.7$. Problem units are identified as units 400 and 2200, whose observed failure rates greatly exceed predictions (e.g., by approximately $k > 30$), with units 100 and 2500 tentatively identified as suspected marginal applications. Unit 100, based on only one failure, would be classified as a "suspected" problem until further flight test time is accrued before initiating any corrective action. By reducing the failure rates in units 400, 2200, and 2500, a 2 to 1 improvement should be achieved in overall equipment MTBF (e.g., from current MTBF ≈ 42 hours, to MTBF > 80 hours). This justifies an engineering investigation of these few problem areas to determine the underlying failure causes needing corrective action.

This illustration of empirical design evaluation indicates the validity of reliability improvements through the reduction of highest unit failure rates.

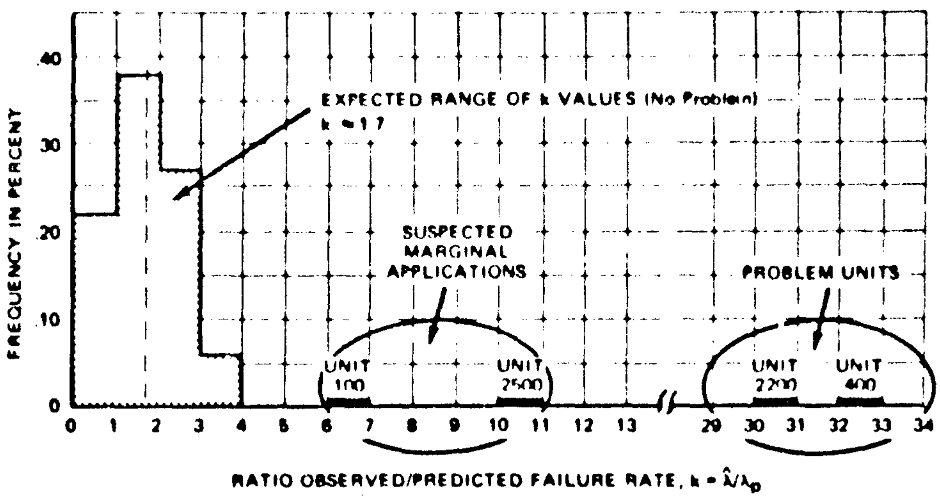

Figure 4. Distribution of Units According to Observed Versus Expected Failure Rate

(3) Investigation of Failure Modes

- Hardware Failure Modes

In general, hardware failure modes and causes do not vary appreciably among analog functions of different types of avionics equipment, i.e., in distribution among component (unit, module, assembly, part, etc.) failure modes manifested in performance malfunctions observed as "outside of tolerance limits" or "inoperative". These failure modes are due largely to inadequate design safety margins because of insufficient "derating" of parts (or their protection) against excessive exposure to application or environmental stresses. Figure 5 represents a typical design margin problem underlying most avionics hardware failures. Even though the initial (t_0) distribution of design characteristics may satisfy equipment performance requirements, variation of the design characteristics (during operating time) is reflected in equipment performance variation and performance failure. Perhaps about half of these failure modes have been correctable by organizational maintenance through alignment or adjustment, half by repair or replacement of the responsible item (e.g., circuit or part replacement).

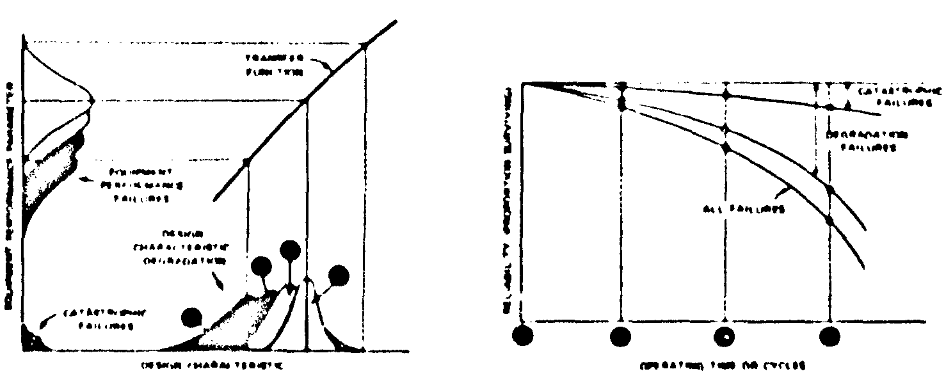

Figure 5. Fundamental Relationship Between Equipment Performance and Design Characteristic Behavior

Figure 6 illustrates this type of problem related to a simple amplifier circuit where voltage gain (V_0) is primarily dependent on stability of load resistor (R_L) and transistor collector current (I_{CER}), to indicate "circuit" failure rate related to part characteristic variation during normal equipment operation. Variability in circuit gain in this illustrative problem might be minimized through feedback stabilization of I_{CER}, choice of negative temperature coefficient resistor (R_L), or tighter tolerance (e.g., ± 1%) on design value of resistance used in the circuit.

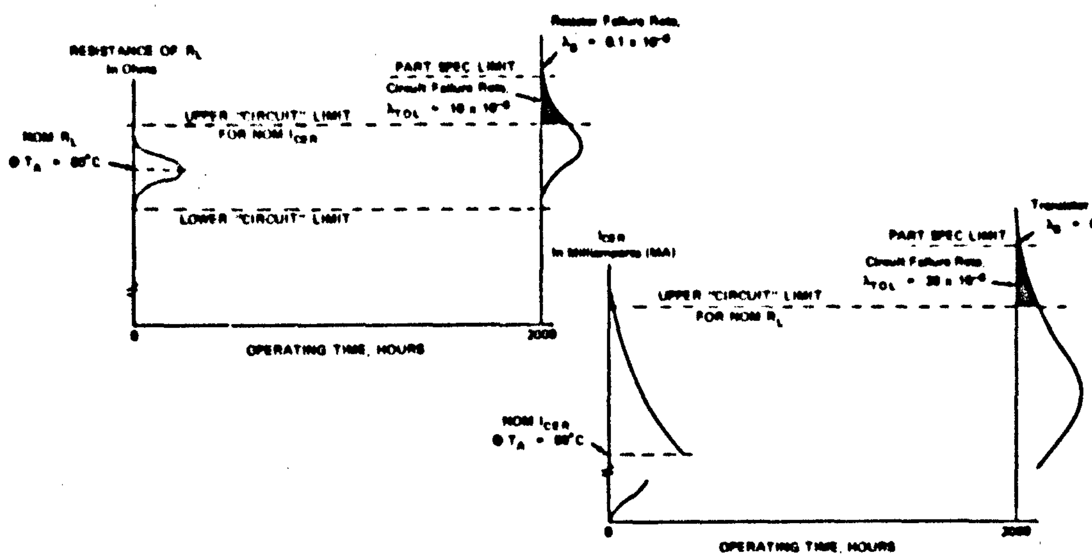

Figure 6. Characteristic Behavior of Parts R_L and Q_1 Under Circuit Conditions, as a Function of Time

Failure modes due to stress-induced part degradation are common in power generators and amplifiers (e.g., power supplies, RF oscillators, power amplifiers, etc.). These failure modes usually show high relative failure rates ($\hat{\lambda}/\lambda_p$), particularly in radar and communications avionics equipment. Failure diagnosis of these failure modes often reveals high power devices (transistors, magnetrons, TWTs, klystrons, RF tubes, and associated passive elements) operating near or exceeding their maximum ratings. A conventional derating curve for these types of devices is illustrated in Figure 7, showing the distribution of applied stresses due to variation in parts characteristics (relative to average design values, $\bar{S}$ and $\bar{T}$). In this illustration, about half of the parts in the representative samples used in the regression analysis fell outside the permissible operating region, as allowed by the part specification. Design correction of these types of problems may involve redesign of electronic circuit, use of alternative choice of parts, modification of thermal control subsystem (e.g., heat sinks to eliminate "hot spots"), or all.

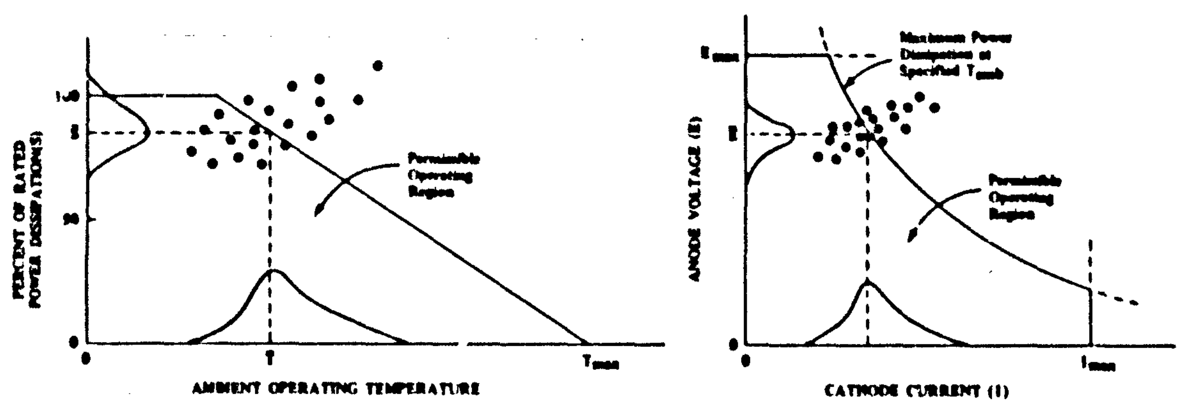

Figure 7. Conventional Derating Curves for Power Devices

- Software Failure Modes

  So-called "software" interface problems are often encountered in central avionics computers used for programmed system operation, sensor data processing, and system checkout. Some software problems are not easily identified in field failure reports. For example, memory deterioration in the computer may be related to harmonic content, spikes, etc., of the primary power source, active memory may be completely lost if aircraft generators are switched in flight or if generators drop load. In some systems, the operational programs have no "malfunction" readouts, so malfunctions can only be detected by go/no-go lights or by incorrect display of tactical information. In these cases, the computer will attempt to "play", even using erroneous input data from an equipment which had malfunctioned. In some cases, tapes may not be interchangeable among all aircraft due often to differences between tape and equipment timing, i.e., certain oscillator and flip-flop modules may work with one tape and not with another.

- Anomalies

  Failures classified as "anomalies" are often traceable to inadequate design tolerance margins at internal input/output interfaces (e.g., between parts, circuits, units, etc.) within the equipment, and interactions with externally flight-induced environmental or operating conditions which exaggerate the inadequacy of these tolerance margins. If these "interactive" conditions disappear on landing, the related tolerance problem also disappears and usually cannot be repeated in post-flight checkout or maintenance. For example, in a typical avionic equipment, approximately 85% of observed anomalies were found "non-defective" by post-flight checkout (in the absence of the in-flight interactions). About 10% of the reported anomalies were attributed to errors in diagnostic test procedures (and thus not chargeable to the basic avionics equipment). Approximately 5% of all anomalies were traceable to procedural errors in equipment operation. Thus, the vast majority of anomalies are caused by equipment (output) performance variation (including intermittent performance) and are best identified through adequately instrumented flight tests or ground-based equipment testing under simulated flight-test conditions.

  In the past, most anomalous failures generated under flight simulated environmental testing were traced to the same types of failure causes described under the hardware failure definitions given earlier. Moreover, we have also observed that anomalous failure rate decreases in proportion to decrease in hardware failure rates as the latter underlying causes are corrected.

In conclusion, significant improvement in avionics reliability (e.g., upward of 10-to-1 growth in MTBF) is feasible in future equipment. However, conventional analytical design procedures alone are not yet adequate for precise identification and drastic reduction of potential equipment failures and tolerance/interaction problems in new avionics designs. More extensive (and intensive) empirical design evaluation techniques must be applied in a formalized, iterative design-verification-design approach to failure-mode/cause detection and correction. The major effort in this empirical design approach should be concentrated in development testing where "feedback" is most effective. This approach should continue in production and operational phases of the life cycle, through the use of feedback from operational data (failure reports).

The amount of design evaluation testing required to achieve a given level of specified reliability (MTBF) beyond the current reliability (MTBF) status in a program can be accurately estimated (within bounds) for purposes of acquisition planning and program control in future systems.

PANNES AFFECTANT LA FIABILITE DES EQUIPEMENT ELECTRONIQUES DE BORD

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0- INTRODUCTION -

On sait que pour obtenir des équipements de bonne fiabilité, on doit faire des efforts à tous les niveaux de la vie de l'équipement : conception et définition du projet, fabrication du matériel, utilisation opérationnelle. Cependant ces efforts ne doivent pas être faits de façon isolée ; il convient de connaître le résultat de ces efforts ; autrement dit, le système doit fonctionner en boucle fermée. Il faut donc mettre en place des moyens permettant de connaître la fiabilié réelle en exploitation et les pannes affectant cette fiabilité.

Dans l'Armée de l'Air française, il a été mis en place un Système Automatique d'Information Technique (SAIT) dont le document de base, la FIT (Fiche d'Intervention Technique), est établi chaque fois qu'une panne ou une anomalie quelconque apparait lors de l'utilisation d'un équipement. Entre autres applications, ce système d'information facilite l'introduction de Clauses de fiabilité garantie dans un certain nombre de contrats d'achats d'équipements électroniques de bord. L'application de ces clauses a été une occasion remarquable d'analyse de la fiabilité réelle en exploitation.

Nous allons donc décrire ce système automatique d'information technique, indiquer le principe et les conditions d'applications des clauses de fiabilité garantie. Nous pourrons enfin examiner les principaux résultats que cela a permis d'obtenir au niveau de la fiabilité réelle des équipements et de l'analyse des pannes affectant cette fiabilité.

I - RECUEIL ET EXPLOITATION DES FAITS TECHNIQUES -

I.1. Les faits techniques .

Les informations concernant l'exploitation des équipements électroniques en service dans l'Armée de l'Air sont de plus en plus prises en compte par un Système Automatisé d'Information Technique (SAIT). Ce système regroupe tous les Faits Techniques intervenant pendant la période d'exploitation opérationnelle des systèmes mis en oeuvre par l'Armée de l'Air. C'est donc le système d'information permettant de connaître les défaillance des équipements électroniques. On dit qu'il y a "Fait Technique" chaque fois qu'une intervention a lieu sur un matériel, à titre correctif ou préventif. Les informations correspondantes sont recueillies sur un document de base, la Fiche d'Intervention Technique (FIT). C'est donc grâce à ce document de base qu'il est possible au technicien de connaître les informations relatives à la fiabilité réelle de l'équipement auquel il s'intéresse. Ces informations sont indispensables pour l'amélioration de la fiabilité de l'équipement considéré ; ils donnent également des informations indispensables pour de nouvelles générations d'équipement. Nous allons donc examiner successivement comment s'effectuent le recueil, le traitement et l'exploitation des

Faits Techniques, permettant l'étude des pannes en fonctionnement réel.

Auparavant, il faut expliquer davantage ce qu'on appelle "Faits Techniques", et comment ces faits techniques sont identifiés et classés.

Pour ce qui intéresse le domaine de la fiabilité, on appelle "Fait Technique" un évènement qui nécessite une intervention corrective pour éliminer une anomalie constatée dans la vie d'un matériel et pouvant compromettre soit son utilisation (par exemple présenter un risque au plan de la sécurité), soit ses performances (par exemple, rendre le matériel incapable de remplir sa mission), soit sa maintenance (par exemple, en augmentant les charges de celle-ci).

Le fait technique est identifié de la façon suivante :

- L'identification précise du matériel concerné,
- Sa localisation exacte,
- La nature de la manifestation (rupture : dérive des performances ; ...)
- Sa cause (composant défaillant ; défaut de fabrication ; sa cause extérieure ; ...)
- Ses conséquences.

Les faits techniques sont aussi classés par leur gravité. On distingue 3 niveaux de gravité :

- Gravité 1 : le fait technique met en cause la sécurité des vols ou des personnels, ou a des conséquences graves au plan opérationnel.
- Gravité 2 : le fait technique met en cause la disponibilité des matériels
- Gravité 3 : on regroupe sous cette rubrique tous les autres faits techniques relatifs à la vie ou à la maintenance du matériel, et dont les conséquences sont moins importantes qu'au niveau 1 et 2.

I.2. Recueil des faits techniques.

Le recueil des faits techniques est la fonction qui consiste en la saisie des informations techniques élémentaires au niveau de l'utilisateur. Ce recueil a une grande importance car, de lui, dépendent l'aboutissement et la qualité des études techniques, en particulier en matière de fiabilité, par l'analyse qualitative et statistique des défaillances. En particulier, il doit être systématique et précis.

Ensuite, par exploitation et traitement ultérieurs, on établira des informations plus élaborées (états d'analyse et de synthèse) à partir de ces faits techniques élémentaires.

Le document de recueil des faits techniques est la FIT (Fiche d'Intervention Technique). C'est un imprimé format standard (21 x 29,7 cm) présenté sous forme de liasse de 4 feuillets

autocopiants, qui auront chacun un destinataire différent ; en particulier un de ces feuillets sera adressé au Centre de Calcul responsable du traitement automatique.

La FIT comprend 2 parties :

- partie de gauche : on y trouve des informations écrites en code, pour être mises en mémoires et traitées automatiquement comme on le verra plus loin. Les informations comprennent les éléments suivants :
  - date et unité opérationnelle concernée,
  - type et identification de l'aéronef support de l'équipement,
  - équipement concerné, avec identification et temps de fonctionnement,
  - circonstances de l'avarie (en vol, au sol, ...) et nature de l'intervention (dépose, test automatique, ...)
  - constatations, gravité, conséquences pour la mission (annulée, retardée, ...)
  - causes de la défaillance.

  Ces éléments sont donnés par la FIT "initiale" émise par l'utilisateur dès l'apparition de l'anomalie ; quand il y a réparation, le réparateur établit une FIT "réponse" qui donne, en complément des informations précédentes, les éléments suivants :
  - renseignements relatifs à la réparation, par exemple : panne imputable ou non au matériel,
  - nature des modifications apportées.

- partie de droite : cette partie "observation" est réservée à la description détaillée (non codée) des constatations faites, des recherches de panne effectuées, des causes présumées de la panne, des mesures prises, des suggestions ... les renseignements sont particulièrement utiles pour une étude ultérieure de fiabilité par analyse des défaillances.

I.3. Traitement et exploitation des faits techniques.

Le traitement des faits techniques est de plus en plus effectué de façon automatique à l'aide de calculateur. Il a pour objet la centralisation, la mise en mémoire et le tri des informations techniques recueillies grâce au FIT et d'en déduire des informations plus élaborées aux plans techniques, opérationnels et logistiques. Ces informations sont regroupées dans différents documents, qui peuvent être périodiques ou établis à la suite d'une demande particulière.

Pour ce qui concerne la fiabilité, deux documents (ou "états") sont pricipalement utilisés :

- Etats de synthèse

  Ils sont établis selon une périodicité trimestrielle ou annuelle. Ils donnent une vision globale de la fiabilité au niveau d'un système d'armes (avion par exemple). Pour chaque équipement ou sous-ensemble important, on trouve : le nombre d'heures de vol, le nombre d'équipements en fonctionnement, le nombre de FIT émises et de défaillances confirmées, le MTBF

"apparent" (relatifs aux heures de vol) et le taux de défaillance.

$$\text{MTBF apparent} = \frac{\text{nombre d'heures de vol x quantité par avion}}{\text{nombre de défaillances confirmées}}$$

Ces états sont diffusés à l'Etat-Major et aux Services Techniques, pour connaître la fiabilité des équipements sur les différents aéronefs. Ils permettent :

- de comparer la fiabilité (MTBF) des différents équipements d'un avion,
- de connaître l'évolution avec le temps du MTBF de chaque équipement.

. Etats d'analyse

Pour la fiabilité et l'analyse des pannes affectant les équipements, l'état le plus communément utilisé est un document intitulé "CLASDEF" ou "état de classement des défaillances par cause de panne". Cet état regroupe dans un seul document les différentes FIT émises pour un équipement donné. Pour chaque équipement, ontrouve donc des renseignements sur les constatations faites et la (ou les) causes de la panne ; ces informations ont été tirées des FIT que l'on a décrites précédemment.

L'état de classement des défaillances par cause de panne estutilisé par les Services Techniques, en liaison avec les industriels,pour examiner les circonstances des avaries, les causes de ces avarieset déterminer les éléments critiques d'un équipement. C'est donc le document es entiel permettant l'analyse des pannes en exploitation des équipements électroniques de bord. C'est aussi le document de base pour l'introduction des Clauses de fiabilité garantie dans les contrats.

En effet, à l'aide de cet état d'analyse, une Commission composée de représentants de l'Etat-Major, des Services Techniques et de l'industriel fabricant l'équipement, examine les interventions effectuées et détermine en particulier si les pannes sont ou non imputables à l'équipement. Connaissant par ailleurs le nombre d'heures de vol des avions sur lesquels l'équipement est monté et compte tenu d'un coefficient heures de vol / heures de fonctionnement, il est aisé de déterminer le MTBF du matériel.

2 - CLAUSES CONTRACTUELLES DE FIABILITE -

Le Système Automatique d'Information Technique, partant de l'information élémentaire donnée par la FIT, aboutit à des informations élaborées consignées dans des Etats de synthèse et d'analyse, et concernant la fiabilité en exploitation et l'analyse des pannes. Grâce à ces informations, il a été possible d'introduire des Clauses de fiabilité garantie dans des contrats d'achats d'équipements électroniques de bord. Les conditions d'applications de ces clauses ont été l'occasion d'analyser finement lespannes, qualitativement et quantitativement, apparaissant en exploitation réelle.

2.1. Principe des Clauses de fiabilité garantie.

Par les Clauses de fiabilité, l'industriel fournisseur de l'équipement s'engage à obtenir une valeur N de MTBF en exploitation réelle (par exemple N = 800 h pour un Tacan). Cette valeur contractuelle est fixée après discussion entre fournisseur et client ; elle est souvent de l'ordre de 80 % de la valeur obtenue par les calculs prévisionnels. Parfois, elle est fixée après des essais de fiabilité en laboratoire.

Dans le cas où la valeur contractuelle N n'est pas obtenue en fonctionnement réel l'industriel doit effectuer gratuitement toutes les corrections et modifications nécessaires pour atteindre l'objectif, sur les matériels à livrer et également sur ceux déjà livrés ; ces modifications ont pour but de remédier aux pannes systématiques.

D'autre part, si la valeur obtenue réellement est inférieure à N - 20%, l'industriel s'engage à effectuer toutes les réparations gratuitement (pièces de rachanges ; mains d'oeuvre ; déplacement..)

Cette garantie de MTBF est assurée en principe pour 5 ans à partir de la livraison.

2.2. Conditions d'application.

La fiabilité de l'équipement est représentée par son MTBF opérationnel. Ce MTBF opérationnel est établi périodiquement (tous les 3 mois en principe) à partir des états d'analyse et de synthèse de PIT, sur tous les équipements en service du type considéré. Une commission de spécialistes composée de représentants des utilisateurs, du Service Technique client et de l'industriel fournisseur, retient les pannes directement imputables au matériel et établit le MTBF opérationnel pour la période considérée.

L'établissement du MTBF demande la connaissance du nombre de pannes et du nombres d'heures de fonctionnement.

Le nombre d'heures de fonctionnement est celui réalisé par tous les équipements en service. Il est lu sur des compteurs horaires ; dans le cas où il n'y a pas de compteur horaire, on détermine les heures de fonctionnement à partir des heures de vol, par application d'un coefficient fixé à priori, et qui dépend du type d'avion et du type d'équipement considéré.

Les pannes prises en considération sont celles qui sont imputables au matériel ; elles englobent toutes les anomalies et fonctionnements défectueux qui empêchent l'équipement d'avoir des performances opérationnelles stisfaisantes et de remplir sa mission.

Les pannes imputables comprennent donc :

- Les défaillances techniques de pièces ou composants, même si les pièces ou composants satisfont aux exigences qui leur sont imposées par le dossier de fabrication.
- Un mauvais fonctionnement quelconque décelable au banc d'essai, dans les conditions extrêmes d'utilisation prévues aux clauses techniques et dont la cause directe est intermittente ou

inconnue,

. La défaillance imputable à plusieurs pièces de types différents qui doit être considérée comme constituant plusieurs défaillances, si chaque pièce considérée séparément empêche d'atteindre les performances satisfaisantes. En revanche, elle doit être considérée comme une défaillance unique si chaque pièce ne peut à elle seule, provoquer la défaillance de l'équipement .

. Les défaillances entraînées par une mauvaise conception.

. Les défaillances entraînées par une fabrication défectueuse.

. Les défaillances imputables à tout défaut des règlages effectués en usine.

En revanche, on ne retient pas pour la détermination du MTBF :

. Les fonctionnements défectueux ou anomalies dûs à des erreurs de manipulation, à des procédés de contrôle, de règlage, d'installation non conformes.

. Les défaillances résultant directement d'une autre défaillance déjà décomptée, si elles apparaissent avant un délai de 50 heures après la première défaillance.

Le MTBF est garanti dans les conditions d'utilisation suivantes :

. L'équipement ne doit pas être utilisé de façon continue dans les conditions climatiques extrêmes.

. Les tensions d'alimentation et les transitoires ne doivent pas excéder des limites autorisées,

. La compétence du personnel effectuant les opérations de détection de panne et d'échange de sous-ensemble doit être suffisante pour qu'il n'y ait ni fausse manoeuvre ni insuffisance dans le travail effectué.

. Les composants dont la durée de vie arrive à expiration doivent être remplacés.

2.3. Résultats obtenus.

Cette clause de fiabilité garantie a déjà été introduite dans de nombreux contrats d'achat d'équipements de radiocommunication ou de radionavigation. L'expérience est encore récente et on rencontre quelques difficultés au niveau de l'application. Il y a pratiquement deux types de difficultés : les premières viennent du fait qu'il est très difficile de connaître le nombre exact d'heures de fonctionnement : par exemple, difficulté de relever des compteurs horaires sur des équipements installés au fond d'une soute, problème pour noter les heures de fonctionnement au banc d'essai, variation selon les types d'avion et les profils de mission ; les secondes difficultés viennent du fait que, lors de la discussion entre utilisateur et fournisseur pour savoir si une panne est imputable ou non à l'équipement, certains cas litigieux

sont difficiles à trancher. Mais globalement le bilan est très positif ; il semble en particulier que l'intéressement financier est un argument décisif pour sensibiliser les industriels aux problèmes de fiabilité ; de plus, l'analyse très détaillée qui est faite pour chaque panne est un facteur d'amélioration de la fiabilité, tant pour l'équipement considéré, que pour de futurs équipements.

2.4. Maintenance forfaitaire.

Outre cette clause de fiabilité garantie dont on vient d'expliquer le principe, les modalités d'applications et les résultats, on a essayé, pour d'autres équipements, d'introduire une clause dite de "maintenance forfaitaire". Le principe est de fixer forfaitairement le montant annuel des coûts de réparation et de maintenence ; ce montant annuel est établi en fonction d'un coût unitaire de réparation, du nombre d'heures de fonctionnement annuel et du MTBF contractuel . Si le MTBF opérationnel est supérieur au MTBF contractuel, le bénéfice de l'industriel est augmenté; dans le cas inverse, bien sûr, il est pénalisé. Ce type de clause paraît séduisant car il allège les formalités administratives et est stimulant pour obtenir des efforts en vue d'une meilleure fiabilité. Cependant, ce type de clause en est encore au stade de tentative préliminaire et nous ne disposons pas encore d'expérience suffisante pour juger de son intérêt réel, de ses résultats et de ses difficultés d'application.

3 - ANALYSE DES PANNES EN EXPLOITATION RELLE -

Comme on vient de le voir, les clauses de fiabilité garantie ont été jusqu'à présent surtout appliquées dans les contrats d'achat d'équipements de radionavigation et de radiocommunication (TACAN, VOR-ILS, Emetteur-récepteur V/UHF, Marker, ...)

Grâce à l'analyse des Etats d'analyse de défaillances et de leur examen lors des réunions de la Commission de spécialistes,il est possible de beaucoup mieux connaître les types de pannes affectant la fiabilité des équipements électroniques de bord.

Il faut donc revenir sur la notion de panne. Pour être prise en compte pour la détermination du MTBF, la panne doit avoir été détectée chez l'utilisateur et entraîner une intervention : ce premier point aboutit, comme on l'a vu, à l'établissement d'une FIT. Ensuite, elle doit être imputable au matériel : c'est le travail de la commission de spécialistes. On distingue donc pannes "imputables " et pannes "non imputables". Seules les premières sont retenues pour le calcul du MTBF.

3.1 Pannes non imputables à l'équipement.

On peut avoir une panne non imputable à l'équipement considéré lorsqu'elle est provoquée par d'autres équipements ; c'est un problème d'interface, et on a rencontré effectivement quelques cas où la panne d'un équipement peut entraîner celle d'un autre équipement.

Mais, le plus souvent, les pannes non imputables sont dûes à des conditions anormales d'utilisations ; problème d'alimentation électrique ; température anormalement élevée ; conditions de vibrations ne correspondant pas au profil théorique décrit dans les spécifications, ... On peut citer un exemple particulier : à la suite de litige sur la température de fonctionnement, on a pris la mesure suivante : des pastilles "Thermocolor" ont été fixées à certains endroits de l'équipement ; on a ainsi constaté que la température relevée était supérieure à ce qui était spécifié ; en conséquence, les pannes correspondantes n'ont pas été imputées à l'équipement.

Il existe aussi des interventions techniques signalées par les FIT qui ne sont pas retenues dans le calcul du MTBF car elles sont dûes à des erreurs humaines de manipulation, soit au niveau de l'emploi opérationnel, soit au niveau de l'installation ou de la maintenance.

3.2. <u>Pannes imputables au matériel.</u>

Ce sont bien sûr les plus nombreuses et celles qui nous intéressent ici. Le système Automatique d'Information Technique que nous avons décrit est un puissant outil d'analyse et de synthèse pour une meilleure connaissance de la fiabilité et l'examen des pannes qui l'affectent. De nombreuses études statistiques sont possibles. On ne donnera ici que quelques exemples illustratifs.

Par exemple, il est toujours intéressant de connaître les statistiques donnant l'origine des pannes. On a trouvé ainsi, pour un émetteur-récepteur :

- 78 % des pannes proviennent de composants défectueux.
- 17 % des pannes proviennent de défauts de fabrication ou de conception.
- 5 % des pannes proviennent de déréglage.

On peut également obtenir une répartition plus fine des défaillances. Sur un autre équipement on a constaté la répartition suivante :

- 56 % des pannes sont dûes à des composants
  - 8 pannes dûes à des circuits intégrés
  - 121 " " aux transistors et diodes
  - 18 " " aux quartz
  - 13 " " aux selfs
  - 47 " " aux condensateurs
  - 15 " " aux potentiomètres et résistances
  - 26 " " à d'autres composants
- 30 % des pannes sont dûes à la fabrication
  - 47 pannes dûes à des soudures
  - 34 " " à des contacts
  - 20 " " à des courts-circuits
  - 30 " " aux câblages
- 14 % des pannes sont dûes à des déréglages.

Il est intéressant de noter, et ce fait est assez général que l'on constate une certaine stabilité dans la répartition de l'origine des pannes entre : composants, fabrication, dérèglages.

Il est aussi possible de connaître la répartition par sous-ensemble d'un équipement ; on a trouvé la répartition suivante pour un émetteur-récepteur V/UHF :

22 % : chassis électrique
13 % : standard de fréquence
29 % : bloc émetteur
3 % : oscillateur de transposition
6 % : préamplificateur de modulation
4 % : bloc récepteur
13 % : bloc basse-fréquence et silencieux
6 % : commande par varicap
4 % : alimentation

A partir de ces résultats, on a pu porter une attention particulière au bloc émetteur dans lequel un transistor causait 20 % des pannes totales.

L'exploitation des faits techniques, avec ce quelle donne pour la connaissance détaillée des pannes affectant la fiabilité, s'est révélée être d'un intérêt très grand. Outre la finalité première qui était la vérification de clauses de fiabilité contrôlée elle apporte des avantages aux plans suivants : elle permet de mieux connaître les conditions d'emploi et d'environnement réels, et ainsi d'en éliminer les anomalies ; elle met en évidence les pannes répétitives, les modules particulièrement critiques, les composants mauvais, les défauts de fabrications ou de conception, et ainsi, après y avoir apporté les remèdes adéquats, permet d'améliorer la fiabilité. Par ailleurs, elle donne de nombreuses informations qui seront utilisées avec profit pour la conception, le développement et la fabrication des équipements futurs.

4 - CONCLUSIONS -

Un système d'information donnant une connaissance globale et analytique de la fiabilité en exploitation est un outil indispensable de promotion de la qualité. Il permet l'introduction de clauses de fiabilité garantie, élément décisif pour intéresser le fournisseur, et moyen efficace pour optimiser le critère "coût-fiabilité". Fondamentalement, un tel système d'information permet de boucler le plan de construction de la fiabilité, en donnant l'origine et la nature des pannes rencontrées en fonctionnement réel.

Les causes d'une mauvaise fiabilité pour les équipements d'avionique se situent au niveau de la conception, de la fabrication et de l'utilisation. Plus précisément, on rencontre surtout :

- au niveau conception : préoccupation de la performance au détriment de la fiabilité ; recherche de la nouveauté plutôt que de la sécurité ; hâte et inexpérience.
- au niveau fabrication : oubli de la fiabilité pour diminuer le prix ; insuffisance du programme de fiabilité ; différents facteurs humains.

- au niveau utilisation : souci du coût initial plus que du coût total mauvaise définition des conditions d'emplois et méconnaissance de l'environnement ; intervention inadaptée.

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TABLEAU 5

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DESTINATAIRE CGMTAA 28200 CHATEAUDUN AIR

FICHE D'INTERVENTION TECHNIQUE 51

ORIGINE — Base — de échelon — Date

SUPPORT — Désignation — Code — N° série — Cod. Act. — Act. dep. RG

S/SUPPORT — Code — N° série — Cod. Act. — Act. dep. RG

MATÉRIEL CONCERNÉ 52
Nomenclature — Structure technologique
Référence fabricant
Désignation — Code fabricant
Repère topologique — N° de série — Nbre de RG
Code activité — Activité depuis RG — Activité totale

CIRCONSTANCE AVARIE 53
Exploitation sol — Exploitation vol — Lancement de stockage — Entretien périodique
Type de VP — Schéma — N° opération — Repère tâche

INTERVENTION SUR MATÉRIEL CONCERNÉ
Sans dépose — Avec dépose pour dépannage — modification
N° fant. conventionnel — Heures de fonctionnement — vérification sur ordre particulier

CONSTATATIONS — Gravité — Code avarie — Conséquence pour la mission

CAUSE PRINC. DE LA DÉFAILLANCE 54
Nomenclature
TCI — Planche — Repère — Code fabricant
Référence fabricant

CAUSES

RENSEIGNEMENTS RELATIFS A LA RÉPARATION 55
Bon fonctionnement — Non reproduit au sol — Non imputable au matériel
Matériel remis en état — Date — Retards pour motif
PROPOSITIONS — Date — Envoi en réparation — Élimination
Expertise — Examen technique — Examen de garantie
Numéro bon modèle 63

MODIFICATIONS APPLIQUÉES

MATÉRIEL REMONTÉ 56
Nomenclature
Référence fabricant
N° de série — Nombre de RG — Code fabricant
Activité depuis RG — Activité totale

POUR FIT COMPLÉMENTAIRE ET FIT RÉPONSE
Rappel N° nomenclature FIT initiale

Fiche d'incident : NON				OBSERVATIONS
OUI — Numéro				
NOMS ET VISAS				

FAILURES AFFECTING RELIABILITY OF AVIONIC SYSTEMS

by

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0. INTRODUCTION

It is now a proven fact that the development of high reliability equipment demands efforts at all the stages of the equipment life project design and definition, manufacturing of the material operational use. However, such efforts must not be made separately, as their results have to be known ; in order words, the system must operate on a closed-loop basis. Therefore, means of determining the actual reliability of a system under operational conditions and of detecting the failures affecting reliability have to be implemented. Such means are indispensable to improve the reliability of the equipment considered ; they also provide information which is indispensable to develop new generations of equipment.

Within the French Air Force, an Automatic System of Technical Information (French acronym : SAIT) has been set up, and a basic document, the Technical Action Form (French acronym : FIT) is drawn up every time any failure or anomaly is observed when an equipment is being used. Among other applications, this information system has permitted the introduction of guaranteed reliability clauses into a number of contracts for the purchase of airborne avionic equipments. The application of such clauses provided an excellent opportunity for analysing actual reliability during the operation of equipments.

This automatic system of technical information will be described, and the principle and conditions of application of guaranteed reliability clauses will be discussed. Finally the main results obtained through this system as regards the actual reliability of equipment and the analysis of the failures affecting reliability, will be reviewed.

1. COLLECTION, ANALYSIS AND UTILIZATION OF TECHNICAL FACTS

1.1. Technical Facts

The handling of information on the utilization of electronic equipments within the Air Force is more and more frequently entrusted to an automatic system of Technical Information (SAIT). This system collects and centralizes all the Technical Facts occurring during the service life of the systems used by the Air Force. This is therefore the Information System through which the failures of electronic equipments can be known.

A technical Fact is said to take place every time corrective or preventive action is carried out on a piece of equipment. The corresponding information is recorded on a basic document, the Technical Action Form (FIT). It is therefore this basic document which supplies to the technician the information relative to the actual reliability of the equipment with which he is concerned. We will examine successively how Technical Facts are collected, processed and used, thus making it possible to investigate failures occurring in the course of actual operation.

First of all, the above mentioned "Technical Facts" should be defined with more accuracy, as well as the methods used for their identification and filing.

In the field of reliability, we call a "Technical Fact" an event which requires corrective action to eliminate an anomaly observed during the service life of a piece of equipment and likely to impair either its use (for instance by endangering its safety), or its performance (for instance by making the equipment unsuited to its mission), or its maintenance (for instance by increasing the workload involved).

A technical fact is identified according to the following process :

. Accurate identification of the equipment concerned

. Determination of its exact location

. Nature of the breakdown (fracture, performance variation, etc.)

. Its cause (defective component ; manufacturing defect ; external cause, etc)

. **Its consequences**

Technical facts are also classified according to their level of severity :

. 1st level of severity : the technical fact endangers flight or personnel safety, or is attended by serious operational consequences.

. 2nd level of severity : the technical fact imperils the availability of the equipment.

. 3rd level of severity : this level includes all the other technical facts related to the life or maintenance of equipment, and whose consequences are less important than those of levels 1 and 2.

[illegible]. Collection of Technical Facts

Collecting technical facts consists in acquiring elementary technical information from the user. Such data collection is essential for the achievement and quality of technical studies, especially as far as reliability is concerned, as it permits qualitative and statistical failure analyses. It should, above all, be systematic and accurate.

The subsequent handling and reduction of the data derived from these elementary technical facts leads to more elaborate information (analysis and synthesis reports).

The document used for the collection of technical facts is the FIT (Technical Action Form). This standard size printed form (21 x 29.7 cm) includes 4 automatic duplication sheets, each meant for a different addressee ; one of these sheets will be forwarded to the Computation Centre in charge of automatic data processing.

The FIT is composed of two parts :

- Left hand part : this part contains coded information to be stored and automatically processed, as will be explained further on. This information includes the following items :

  . date and operational unit concerned

  . type and identification of the aircraft on board of which the equipment is used

  . equipment concerned, with identification and time in service

  . circumstances of the damage (in flight, on the ground, ...) and type of action taken (removal, automatic test, etc.)

  . facts observed, severity, consequences for the mission (cancelled, postponed, etc.)

  . causes of the failure

The above data are provided by the initial FIT filled in by the user as soon as an anomaly is observed ; when repairs are carried out, the repairer prepares a reply FIT which, as a complement to the preceding information, gives the following data :

  . information on the repair carried out, for instance : failure ascribable or not to the equipment

  . nature of modifications made

- Right hand part : This section, entitled "remarks", is reserved for the detailed description (uncoded) of the facts observed, the trouble shooting carried out, the assumed causes of the failure, the measures taken, the suggestions made, etc. This information is extremely useful for a subsequent reliability investigation with failure analysis.

[illegible].3. Processing and Analysis of Technical Facts

Technical facts are more and more frequently computer processed. The purpose of such processing is to centralize, store and sort out the technical data collected through the FIT's, then to derive from these more elaborate technical, operational and logistic data. These data are in turn recorded in several documents which are published either periodically or at specific requests.

In the field of reliability, two documents (or "reports") are essentially used :

. Synthesis reports

These are prepared every term or every year. They provide a general survey of the reliability of a weapon system (aircraft, for instance). The items listed for each main equipment or sub-unit are : number of flying hours, number of equipments in operation, number of FIT's produced and of confirmed failures, "apparent" MTBF (with regard to flying hours) and failure rate.

$$\text{apparent MTBF} = \frac{\text{number of flying hours x number of device per aircraft}}{\text{number of failures confirmed}}$$

These reports are circulated to the General Staff and the Technical Departments, in order to determine the reliability of equipments on the various aircraft. They provide the means of :

. comparing the reliability (MTBF) of the various equipments of an aircraft

. knowing the development of the MTBF as a function of time for each equipment

. Analysis reports

As regards reliability, and the analysis of failures affecting the equipments, the most commonly used report is a document entitled "CLASDLF" (acronym for the French phrase : report on classification of failures according to their causes). For each equipment, information is provided on the observations made and the cause(s) of the failure ; this information is extracted from the FIT's described above.

The report on the classification of failures according to their causes is used by Technical Departments, in coordination with industrial firms, to investigate the circumstances and causes of damages and identify the critical elements in an equipment. It is therefore the essential document used as a basis for the analysis of airborne avionic equipment failures occurring in the course of operation, as well as for the introduction of guaranteed reliability Clauses into contracts.

As a matter of fact, with the help of this analysis report, a Committee consisting of representatives from the General Staff and the Technical Departments, and of the equipment manufacturer, considers all the action taken and deci .s whether the failures are, or are not, ascribable to the equipment. . owing the number of flying hours of the aircraft on which the equipment is installed, and taking into account a flying hours/hours in service coefficient, it is easy to determine the MTBF of the equipment.

2. RELIABILITY CONTRACT CLAUSES

Starting from the elementary information provided by the FIT, the Automatic System of Technical Information leads to elaborate information recorded in the synthesis and analysis reports and dealing with reliability in service and failure analysis. Such information permitted the introduction of guaranteed reliability Clauses into contracts for the purchase of airborne avionic equipments. The conditions of application of these clauses provided the opportunity of carefully analyzing failures occurring in service, from both qualitative and quantitative standpoints.

2.1. Principle of guaranteed reliability Clauses

Through reliability clauses, the equipment manufacturer undertakes to achieve a value N of MTBF in actual service (for instance, N = 600 hours for a "Tacan"). This contractual value is set after an agreement between the supplier and the customer ; it is often approximately 60 % of the value obtained by prediction calculations. Sometimes it is set on the basis of reliability tests carried out in laboratory.

If the contractual value N is not obtained in actual operation, it falls on the manufacturer to carry out, free of charge, all the corrections and modifications necessary to reach the objective set, both on the equipment to be delivered and on that already delivered ; the purpose of such modifications is to remedy systematic failures.

Besides, should the value actually obtained be lower than N - 20 % , the manufacturer must undertake to carry out all repairs free of charge (spare parts, man-power, travelling, etc.).

As a rule, this MTBF guarantee covers 5 years from the date of delivery.

2.2. Conditions of Application

The equipment reliabi lit is represented by its operational MTBF. This operational MTBF is determined per ically (as a rule, every three months) on the basis of FIT synthesis and an reports, for all the equipments of the type considered which are in A specialists' committee including representatives of the users, from th Technical Service, and the supplier, determines the operational MTBF iod considered, on the basis of the failures directly attributable t ial.

To determine the MT necessary to know the number of failures and of hours in service.

The number of hours ... service is that covered by all the equipments in service. It is given by a time meter ; when there is none, hours in service are determined from flying hours, by applying a coefficient set a priori, which depends on the type of aircraft and equipment considered.

The failures which are taken into account are those ascribable to the components. They include all the anomalies and malfunctions which prevent the equipment from achieving a satisfactory operational performance and fulfilling its mission.

Therefore, such failures include :

- Part or component failures, even if parts and components meet the requirements formulated in the manufacturing specifications.
- Any malfunctioning detectable on a test bench, under the extreme conditions of use provided for by the technical clauses, and whose direct cause is either intermittent or unknown.
- Failures ascribable to several parts of different types, which should be regarded as constituting several failures if the part, considered indiviudally, creates an obstacle to satisfactory performance. On the contrary, it should be regarded as a single failure if each part, considered separately, cannot bring about a failure of the whole equipment :
- Failures induced by defective design.
- Failures induced by defective manufacturing.
- Failures ascribable to any error in the adjustments carried out within the plant. However, the following defects are not taken into account when determining the MTBF :
- Malfunctioning or anomalies caused by handling errors, or incorrect checking, adjustment or setting up procedures.
- Failures resulting directly from another failure already taken into account, even if they take place within 50 hours following the first failure.

The MTBF is guaranteed under the following conditions of use :

- The equipment must not be used continuously under extreme climatic conditions.
- Power supply voltages and transitory phenomena must not exceed the authorized limits.

The personnel in charge of trouble shooting and sub-unit replacements must be competent enough to avoid wrong moves and to perform satisfactory work.

The components whose service life comes to an end must be replaced.

2.3. Results Obtained

This guaranteed reliability clause has already been introduced into many contracts covering the purchase of radiotransmission or radionavigation equipment. However, such experience is still recent, and a few difficulties are encountered as regards details of application ; some of them result from the fact that it is very difficult to know the exact number of hours in service : for instance, difficult reading of time meters on equipments located at the bottom of a cargo-compartment, problems involved in recording hours of operation on a test bench, variation with aircraft types and mission profiles. Other difficulties arise from the fact that when a user and a supplier argue to determine if a failure is, or is not to be ascribed to the equipment, some disputable cases are difficult to settle. However, on the whole, results are very positive ; financial involvement, in particular, seems to be a decisive argument in increasing manufacturers' concern for reliability problems ; besides, the extremely detailed analysis which is performed for each failure contributes to improving reliability, as regards the equipment considered as well as future equipment.

2.4. Contractual Maintenance

Besides the guaranteed reliability clause whose principle, methods of application and results have just been presented, attempts have been made to introduce a so called "contractual maintenance" clause for other equipment. Its principle consists in setting, by contract, the yearly amount of repair and maintenance costs ; this yearly amount is determined on the basis of the unit-price of repairs, of the yearly number of hours of operation, and of the contractual MTBF.

If the operational MTBF is higher than the contractual MTBF, the manufacturer's benefit is increased ; on the contrary, should the reverse be true, the manufacturer is penalized. This type of clause seems attractive as it reduces administrative procedures and stimulates efforts to achieve higher reliability. However, this type of clause is still at the preliminary and tentative stage, and we have not yet acquired sufficient experience to appreciate its real value, its results and the difficulties involved in its application.

3. FAILURE ANALYSIS IN ACTUAL SERVICE

As stated above, up to now guaranteed reliability clauses have been applied essentially to contracts for the purchase of radionavigation and radiotransmission equipments (TACAN, VOR-ILS, V/UHF transmitter-receiver, Marker, etc.).

Through the analysis of failure analysis Reports and their discussion at the meetings of the Specialists'Committee, it is now possible to get better acquainted with the types of failures affecting the reliability of airborne avionic equipments.

Here, the notion of failure should be further specified. In order to be taken into account for determining the MTBF, the failure must have been detected at the user's and must require action ; as mentioned previously, this first step leads to the drawing up of a FIT. Then, the failure must be ascribable to the components ; this decision rests on the Specialists'Committee. Thus "ascribable" failures are differentiated from "non ascribable" ones. Only the first group of failures is taken into account for the calculation of the MTBF.

3.1. Failures non ascribable to the equipment

A failure is not ascribed to the equipment considered when it is created by other equipment ; this is an interface problem, and there have been a few cases when the failure of a given equipment could involve that of another equipment.

However, most frequently, non ascribable failures are due to abnormal conditions of use : power supply problem ; abnormally high temperature ; vibration conditions deviating from the rated profile described in the specifications, etc. A particular example can be quoted here : following a dispute on the operating temperature, the following action was taken : "thermocolor" patches were fixed on to some points of the equipment, and it was possible to verify that the temperature recorded exceeded the specified temperature ; consequently, the corresponding failures were not attributed to the equipment.

There are also some types of technical action, reported by the FIT's, which are not taken into account when calculating the MTBF, as they result from human errors in handling, either in the field of operational use, or in the setting up and maintenance.

3.2. Failures ascribable to the equipment

These failures, the most frequent ones of course, are those with which we are concerned here. The Automatic System of Technical Information described previously is an extremely valuable analysis and synthesis tool for getting a better insight into reliability and a better understanding of the failures which affect it. Many statistical studies can be carried out. Only a few examples will be given here for illustration purposes.

For instance, it is always interesting to know the statistics regarding the origins of failures. For a transmitter-sender, the findings are as follows :

- 78 % of failures result from defective components.
- 17 % of failures result from design or manufacturing defects.
- 5 % of failures are due to maladjustments.

A more accurate distribution of failures can also be obtained. On another equipment, the following distribution was found out :

- 50 % of failures are attributable to components.
  - 8 failures due to integrated circuits
  - 121 failures due to transistors and diodes
  - 18 failures due to quartz
  - 13 failures due to inductance coils
  - 47 failures due to capacitors
  - 15 failures due to resistances and potentiometers
  - 26 failures due to other components

.30 % of failures are attributable to faulty manufacturing

. 47 failures due to welding

. 34 failures due to contacts

. 20 failures due to short circuits

. 30 failures due to wiring

.14 % of failures are attributable to maladjustments

It is interesting to note - and this is a rather general fact - that a certain stability can be observed in the distribution of failure sources among : components, manufacturing, maladjustments.
It is also possible to determine the failure distribution among the sub-units of an equipment ; the following distribution was found for a V/UHF transmitter/receiver :

. 22 % mechanical frame

. 13 % frequency source

. 29 % transmitting unit

. 3 % transposition oscillator

. 6 % modulation preamplifier

. 4 % receiving unit

. 13 % low-frequency unit and silencer

. 6 % varicap control

. 4 % power supply

In view of these results, special attention was devoted to the transmitting unit in which a transistor caused 20 % of the overall failures.
As it provides the means of getting at a detailed knowledge of failures affecting reliability, the analysis of technical facts has proved to be of considerable interest. Apart from its primary purpose, which was the checking of controlled reliability clauses, it offers advantages from the following viewpoints it leads to a better knowledge of real use and environmental conditions, and, consequently, makes it possible to eliminate anomalies ; it reveals repeated failures, particularly critical modules, defective components, design or manufacturing defects and therefore provides the means of improving reliability by applying appropriate remedies. Besides, it supplies a large amount of information which can be used fruitfully for the design, development and manufacturing of future equipment.

4. CONCLUSIONS

An information system providing a general as well as analytic knowledge of the reliability of equipment in service is an indispensable tool for promoting quality. It enables one to introduce guaranteed reliability clauses, a decisive element in arousing the supplier's interest, and an efficient means of optimizing the "cost-reliability" criterion. Fundamentally, such an information system makes it possible to close the loop of the reliability development programme by giving the origin and nature of failures observed in actual operation.
The causes of poor reliability in avionic equipment can be found at the design, manufacturing and utilization stages. More precisely, these causes are essentially the following :

- at the design stage : concern for performance to the prejudice of reliability ; pursuit of novelty rather than safety ; haste and lack of experience.

- at the manufacturing stage : disregard for reliability in order to reduce costs ; insufficient reliability programmes ; various human factors.

- at the utilization level : care for the initial cost rather than for the total cost ; faulty definition of the conditions of use and misappreciation of the environment ; inadequate action.

The author acknowleges with thanks the assistance of Mr. A. Laurenson in drawing up this text.

IMPACT OF RELIABILITY IMPROVEMENT WARRANTY (RIW) ON AVIONIC RELIABILITY

by

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SUMMARY

The Air Force has provided incentives to contractors of new systems to design and produce electronic equipment with low failure rates and low repair costs in operational use. These incentives are included in procurement contracts as Reliability Improvement Warranty (RIW) provisions. The RIW provisions obligate the contractor to accomplish repair and replacement of failed equipment at a fixed price during operational use of the equipment by the Air Force. The contractor also guarantees the mean-time-between-failure of the equipment during the warranty period. RIW is projected to have a significant impact on avionic reliability.

INTRODUCTION

Reliability Improvement Warranty (RIW) contracting is being billed as a new concept in airplane hardware procurement that will lead to improved reliability and reduced support cost, thus putting teeth in the Department of Defense's life-cycle-cost commitments in acquisition contracts. This paper describes

- What Reliability Improvement Warranty (RIW) is
- Why the services are promoting RIW
- Where RIW got its start
- To what equipment RIW is applied
- What an RIW contract contains
- A contractor's response to RIW during proposal development and production phases
- Air Force areas of study toward making RIW a viable concept.

RELIABILITY IMPROVEMENT WARRANTY (RIW) DEFINED

An RIW contract between the U. S. Air Force and a contractor obligates the contractor to accomplish repair and replacement of failed aeronautical equipment at a fixed price during operational use of the equipment by the Air Force. Under RIW, failed equipment is returned to the contractor, and the repair and replacement are accomplished at no expense to the Air Force for a specified duration of flight/operate time or calendar time. The manner in which a typical RIW contract functions is depicted in Figure 1.

Inherent in the fixed-price contract, the Air Force provides an incentive for the contractor to improve the reliability and maintainability of the equipment. If during the course of the warranty period the contractor determines that an equipment change would reduce the number of future repair actions, and that this change coupled with the less frequent occurrence of repairs in the future will result in less contractor money being spent during the remaining warranty period, he can submit this change in a no-cost-to-USAF equipment improvement engineering change proposal (ECP).

Another provision which can be imposed under the RIW contract is the RIW/MTBF guarantee provision. Under this provision the contractor guarantees the equipment Mean-Time-Between-Failure (MTBF) experienced during Air Force operational usage. During designated time periods, the MTBF of the equipment is assessed. If the assessed MTBF is less than the guaranteed MTBF during a time period, the contractor is required to institute corrective action at his expense until the MTBF improves. (Reference 1)

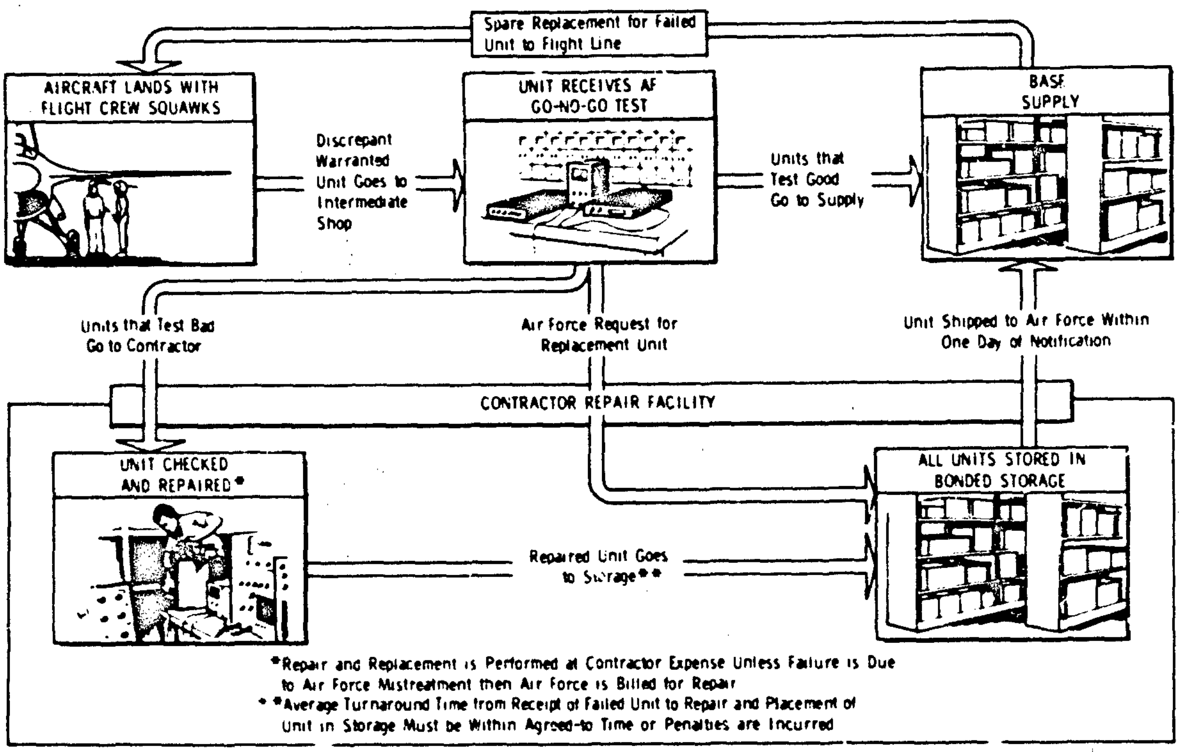

Figure 1 TYPICAL WARRANTY PIPELINE

THE NEED FOR RIW

With Air Force Operations and Maintenance (O&M) costs rising rapidly at a time when the defense budget is being constrained, it is imperative that the Air Force find methods of cost reduction. In the fiscal year 1964, Air Force O&M costs accounted for 21% of the Air Force budget, while in fiscal year 1973, these costs accounted for 27%. The O&M costs are projected to continue to grow and will take an increasingly larger percentage of total Air Force dollars. As more dollars go to O&M costs, less dollars are available for weapon system research, development, and procurement. To slow the trend of increasing O&M costs, contractors must place greater emphasis on cost-effective methods of accomplishing support activities and on increasing the field reliability of equipment.

The concept of RIW was presented to the assistant secretaries of the Military Departments (Research and Development and Installation and Logistics) in August 1974 in a memorandum entitled "Trial Use of Reliability Improvement Warranties in the Acquisition Process of Electronic Systems/Equipments - ACTION MEMORANDUM". The memorandum was released by Arthur I. Mendolia, Assistant Secretary of Defense (I&L), and Malcolm R. Currie, Director, Defense Research and Engineering. The memorandum stated that as part of the Department of Defense's efforts to reduce costs and improve operational reliability, trial application of RIW should be utilized in the acquisition process to help determine the scope and benefits that RIW might have for the Department of Defense.

The objective of the RIW as set out by the Department of Defense is to motivate and provide an incentive to contractors to design and produce equipment that will have low failure rates as well as low repair costs after failure due to field/operational use.

For some time, the Air Force has been trying to get improved reliability and maintainability through procurement methods that include reliability/maintainability programs. These have worked to some extent, but, despite the use of these methods, the Air Force is still plagued with poor equipment reliability and high support costs. Under these methods of procurement the contractor's responsibility for all practical purposes ends with the delivery of the equipment to the Air Force. These methods also put much importance on low procurement price, thus causing contractors to design and develop equipment with the lowest reliability that will pass contract requirements.

RIW represents a new trial concept in Department of Defense contracting with the primary objective of extending the contractor's responsibility to include operational

reliability of equipment during Air Force usage. Past experience indicates that there is reliability growth from time of the initial design to the maturity of equipment in operational usage. With the application of RIW, the contractor is directly involved during this period and should be able to accelerate reliability improvements and minimize the cost associated with incorporating these improvements.

Imposing RIW can serve as a most effective method of closing the information gap between the Air Force usage of equipment and the contractor who controls equipment design. With RIW, the contractor is motivated to find out a lot more about what his equipment is doing in the field and to initiate changes to decrease future failures and thus, to decrease his cost of meeting RIW responsibilities. Under RIW, the contractor becomes actively interested in asset management and the control of problems which are usually thought of as Air Force responsibilities. Turnaround of equipment, which is always vital to the Air Force, is now vital to the contractor also. Under RIW, with contractor direct involvement, the lead time associated with reliability and maintainability improvements should be greatly shortened since further capital investment is not required from the Air Force and the contractor will push the improvement change to decrease his future repair costs.

Department of Defense guidelines for the trial use of RIW during procurement spell out the following potential benefits to the Government and to the contractor:

"Benefits to Government

a. Incentives and responsibility for field reliability are assigned to the contractor.

b. Greater emphasis is placed on the life-cycle-cost approach.

c. The contractor is responsible to keep all units up to the same configuration.

d. There is an increased incentive for the contractor to introduce design/production changes that will increase the MTBF of the equipment and result in reliability growth.

e. An incentive for reduction in repair costs is provided, since any reduction in labor hours or materials used in repairing equipment will increase the contractor's profits.

f. Minimal initial support investment is required by the Government, since the contractor is to provide repair services during the warranty period.

g. RIW usage may reduce requirements for skilled military maintenance and support manpower.

Benefits to Contractor

a. Increased profit potential when field MTBF is improved above pricing base.

b. Multi-year guaranteed business.

c. The contractor becomes more familiar with the operational reliability and maintainability characteristics of his equipment which should help him in obtaining follow-on contracts."

Thus, under RIW procurement, the objective of both the Air Force and the contractor is the same - to reduce the rate of equipment removal and repair. If successful, the Air Force will have a more effective weapon system and the contractor will have reduced the cost of meeting his RIW obligations. The RIW concept provides a means for continuous product improvement by having "reliability" be of equal importance with "functional performance." (References 1, ?)

THE START OF RIW

The forerunner of the RIW concept was the U. S. Navy Failure Free Warranty (FFW) program with Lear Siegler on a two-gyro platform in 1967.

Lear Siegler designed the two-gyro platform for the Navy, and production quantities were delivered in the late 1950s. In the early 1960s, Lear Siegler and the Navy were both overhauling the gyroscopes. In 1967 Lear Siegler proposed the failure-free warranty concept to the U. S. Navy and was put under contract. The proposal

centered around a fixed price to cover overhauls required during a long-term field operating period. The contract included the following:

- The overhaul of inservice gyros - 800 gyros guaranteed for 1500 hours or 5 years whichever occurs first.
- A fixed price based on 33% of reliability improvement over the contract period.
- A specified turnaround time.

Results of the FFW contract were that the gyro's reliability had exceeded expectations and the Navy saved approximately $2 million.

Since the FFW contract with Lear Siegler, the services have initiated RIW contracts on such items as the ARN-XXX TACAN and the major avionics on the F-16. Application of the RIW on the F-16 will be discussed later in this paper. (References 2, 3, 4, 5)

EQUIPMENT TO WHICH RIW IS APPLIED

Not all equipment types are likely candidates for RIW coverage. For example, equipment whose construction precludes the installation of seals or other control mechanisms to prevent unauthorized field repair may not be good candidates. Direction from the Department of Defense as to what equipment types should be considered is included in the RIW guidelines, which were an attachment to the memorandum entitled "Trial use of Reliability Improvement Warranties in the Acquisition Process of Electronic Systems/Equipment." Selected equipment-related criteria for likely equipment types to be covered by RIW contained in the guidelines are presented below:

- The equipment is readily transportable to permit return to the vendor's plant or, alternatively, the equipment is one for which a contractor can provide for field service.
- The equipment is generally self-contained, is generally immune from failures induced by outside units, and has readily identifiable failure characteristics.
- Moderate to high initial support costs are involved.
- Equipment application in terms of expected operating time and the use environment are known.
- The equipment is susceptible to being contracted for on a fixed-price basis.
- The equipment has a potential for both reliability growth and reduction in repair costs.
- A sufficient quantity of the equipment is to be procured to make the RIW cost effective.
- The equipment is of a configuration that discourages unauthorized field repair, preferably sealed and capable of containing an Elapsed Time Indicator (ETI) or some other means of usage control.
- A reasonable degree of assurance exists that there will be a high utilization of the equipment.
- The equipment is one that permits the contractor to initiate no-cost ECPs subsequent to the Government's approval.

EQUIPMENTS INCLUDED IN PRESENT RIW CONTRACTS

The F-16 aircraft contract serves as a good recent example of the application of the RIW concept. A summary description of the F-16 aircraft and a list of that F-16 equipment involved in the RIW provisions of the contract are given in Figure 2. All the equipment listed is electronic equipment, and its selection for inclusion under RIW meets the general Department of Defense selection criteria. Another criterion used in the selection of the F-16 equipment to be included under RIW was the equipment's projected logistic support cost during Air Force usage. A brief presentation of the use of the cost criterion in the selection of F-16 RIW candidates is given in Figure 3. Detailed discussions of logistic support cost analyses on the F-16 are given in a later paper in this volume.

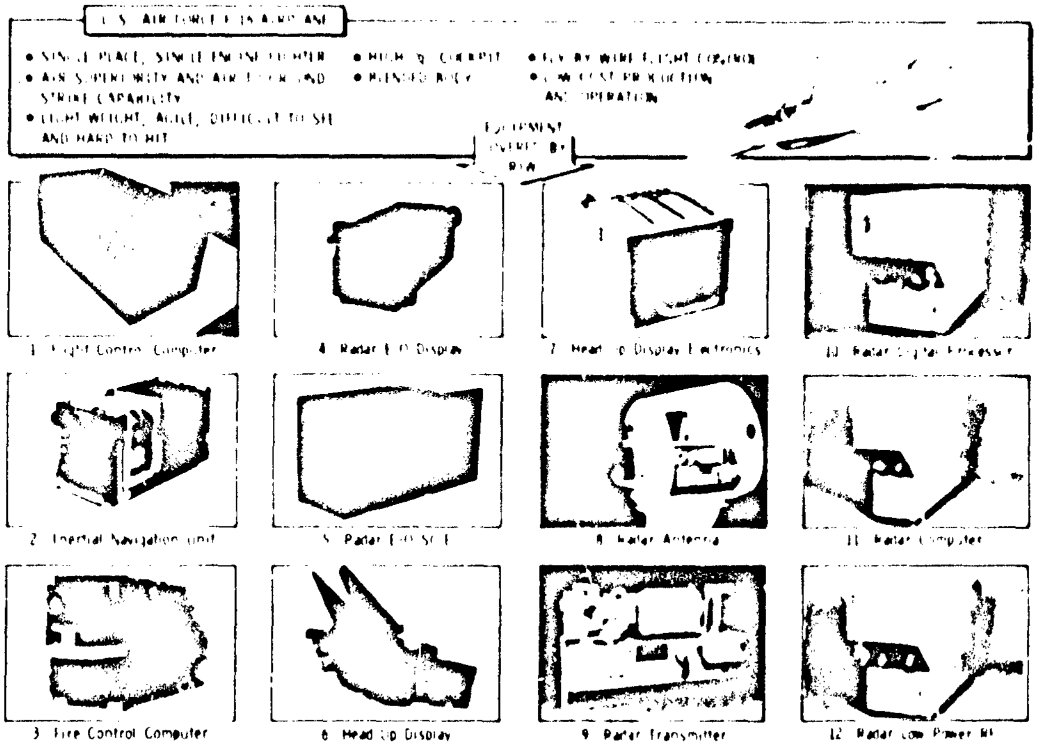

Figure 2 SELECTED F-16 EQUIPMENT ARE INVOLVED IN RIW

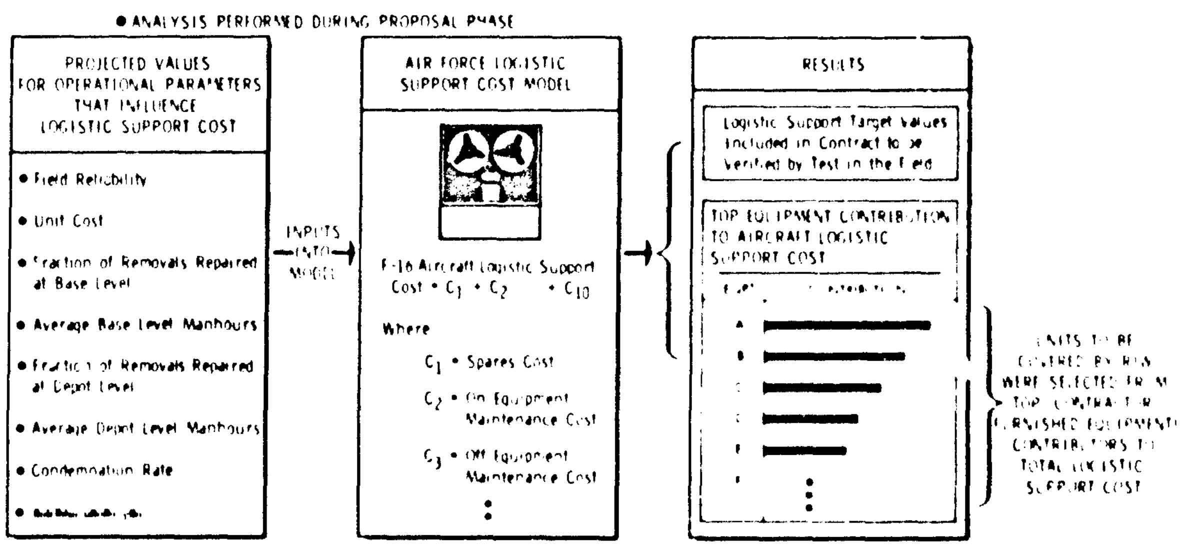

Figure 3 USE OF LOGISTIC SUPPORT COST CRITERION FOR SELECTION OF RIW CANDIDATE

THE CONTENT OF AN RIW CONTRACT

Because specific RIW provisions should be tailored to the weapon system or equipment being warranted, a standard set of specific terms and conditions do not exist. However, the warranty section of the F-16 contract can be reviewed. This review constitutes a summary of the salient terms and conditions of the F-16 contract and will serve to outline the basic ingredients contained in present-day RIW contracting.

F-16 RELIABILITY IMPROVEMENT WARRANTY

The contractor agrees to provide (at firm fixed prices included in the contract) either of two options:

- A 48-month (or 300,000-flight hour) reliability improvement warranty on any or all of the First Line Units (FLUs) listed in Table 1. (This option will be referred to as the RIW option.)
- A 48-month (or 300,000-flight hour) reliability improvement warranty with an MTBF guarantee on any or all of the FLUs listed in Table 1. (This option will be referred to as the RIW/MTBF option.)

TABLE 1. FLU LIST

FLU	FY - Dollars	
	RIW	RIW/MTBF
Flight Control Computer		
Heads-Up Display		
Heads-Up Display Electronics		
Fire Control Computer		
Inertial Navigation Unit		
Radar E/O Display		
Radar E/O Electronic		
Radar Antenna		
Radar Transmitter		
Radar Digital Processor		
Radar Computer		
Radar Low Power RF		

AIR FORCE EXERCISE OF OPTIONS

Any of the options can be exercised on or before production go-ahead. The warranty period starts at delivery of the first production airplane and continues for 48 months of 300,000 flight hours, whichever comes first. In addition, the contractor agrees to negotiate extending the warranty period for additional 24-month periods at the option of the government.

WARRANTY AND REPAIR STATEMENTS

The contractor warrants that each FLU delivered under the production contract or associated separate spares contract will be free from defects in design, material, and workmanship and will operate, when required, in its intended environment in accordance with contractual specifications, for the warranty period set forth. Any FLU that fails to meet the warranty will be returned to the contractor (at Government expense) and will be repaired or replaced (at contractor expense).

The contractor shall not be obligated to repair or replace at no cost to the Government any warranted FLU that is lost or damaged by reason of fire explosion, submersion, flood, aircraft crash, enemy combat action, or tampering by Government personnel, provided there is clear and convincing evidence of such cause. In addition, the contractor shall not be obligated for repair of physical damage caused by mistreatment or tampering by non-contractor personnel. The contractor is not liable for special consequential or incidental damages.

Any failed FLU not covered by warranty that is returned to the contractor will be repaired as directed by the Government for an equitable price/cost adjustment.

CONTRACTOR OBLIGATIONS

In addition to the basic warranty and repair statements mentioned above there is a list of comprehensive contractor obligations included in the contract. These obligations are summarized below.

- All contractor-initiated ECPs for improved reliability and maintainability approved by the Government will be incorporated at no cost to the Government. As each FLU is repaired by the contractor, it will be brought up to the latest configuration. Kits will be provided for unmodified FLU's at the end of the warranty.
- A suitable and prominent display of warranty information will be placed on the surface of each FLU.
- At least one fully operational warranty-repair facility will be maintained at a location to minimize pipeline time. The facility will include a secure storage area for spares.
- Seals will be installed on all warranted FLU's to minimize unauthorized maintenance.

- When a FLU fails, the Government notifies the contractor in writing or by electronic message. Shipment of a replacement spare will be within one working day, but not later than 72 hours after notification.

- The repair, replacement, and/or incorporation of approved reliability and maintainability modifications on all returned FLUs must be completed and FLUs stored in secure storage on a turnaround time average of a specified number of days.

- Actual average turnaround time will be computed in 6-month intervals. If the actual value during a 6-month period is greater than the specified average turnaround time for returned FLU's, a penalty will be assessed. The contractor will lend the Government consignment FLU's if spare shortages occur. The maximum number of consignment spares that are to be provided are determined by an equation in the contract. If consignment FLU's are not provided, a dollar penalty is incurred in accordance with the contract.

- The contractor will include applicable warranty information in all pertinent technical manuals.

GOVERNMENT OBLIGATIONS

There are also Government obligations written into the contract. These obligations are summarized as follows:

- Failures will be verified by the Government, using appropriate procedures and test equipment.

- The Government will provide the contractor with failure circumstance data.

- MIL-STD-794 packaging will be used to the extent possible on shipment of FLUs.

- Failed FLU's will be shipped promptly to the contractor.

- The contractor will be notified of a failed FLU, and shipping instructions will be provided for delivery of a replacement unit.

- The Government will provide the contractor information on accumulated flight hours on F-16 aircraft.

- No-cost Reliability and Maintainability Engineering Change Proposals (ECPs) submitted will be incorporated into the contract "X" days after receipt unless the contractor receives written notification of non-approval by the Government prior to that date.

WARRANTY DATA REQUIREMENTS

The contractor will develop and maintain a data accumulation, processing, analysis, and reporting system capable of providing the data items necessary for implementing any of the provisions of the warranty and capable of providing to the Government data and information on the reliability of a warranted FLU. The internal contractor data system should provide data such as shown in Table 2.

RIW/MTBF GUARANTEE OPTION

If the Government decides to exercise the RIW/MTBF guarantee option, the following provisions apply in addition to those of the basic RIW option stated in prior paragraphs:

- The contractor guarantees that each FLU delivered under the production contract or associated spares contract will achieve an MTBF equal to or greater than that shown in Table 3.

- For this guarantee, MTBF is defined to be total operating hours accumulated on all units during a specified period divided by the total number of failures of all such units during that period.

- For purposes of the MTBF measurement, failures will include all replacement or repair actions performed under the RIW provision except thos repair and replacements covered under the exclusion clause and except any FLU which is returned

TABLE 2. RIW CONTRACTOR DATA ELEMENTS

RIW AND RIW/MTBF DATA
o CONFIGURATION CONTROL DATA o Configuration Control by Serial Number o All Changes to Configuration, Design, Part, T.O., or AGE that Affect Form, Fit, or Function o Changes that Do No Affect Form, Fit, or Function o FLU INITIAL DELIVERY DATA o THE FOLLOWING FOR EACH RETURNED FLU o Date Received by Contractor o Serial Number o ETI Reading o Condition of Unit Based on Initial Inspection o Failure Mode o Probable Failure Cause o Action Taken for Repair o Manhours Expended by Labor Category o Parts and Material Usage o Test Results o Date Stored in Secure Storage Area o Hour and Date of Notification of a Failure o Hour and Date Replacement Unit is Shipped from Secure Storage

and tests out well at the repair facility.

- o For purposes of MTBF measurement, total operating hours will be computed by use of equations in the contract. These equations are based on elapsed operating time from failed units.

- o For each type of FLU, the contractor will make semi-annual measurements of the FLU MTBF achieved over the previous 6 months. The first measurement will be made 6 months after the initial anniversary date. The contractor's obligation terminates when two consecutive measurements yield FLU MTBF values that equal or exceed the guaranteed MTBF values for Period 3, but in no event will the obliga[illegible] terminate earlier than 18 months after initial anniversary date.

- o In the eve[illegible] measured MTBF for any measurement period is less than the guaranteed value, [illegible] contractor will furnish to the Government the following:

  a. Engineering analyses to determine causes of non-conforming MTBF.

  b. Corrective engineering design changes.

  c. Modification of the FLUs, spare FLUs, and/or spare parts, as required, at contractor expense.

  d. Pipeline unit spares as needed by the Government on a consignment (no-charge loan) basis but no greater than a quantity computed by an equation in the contract.

TABLE 3. MTBF GUARANTEE VALUES

FLU	FLU MTBF*		
	PERIOD 1	PERIOD 2	PERIOD 3
	1 THRU 12 MONTHS	13 THRU 24 MONTHS	25 THRU 36 MONTHS
NAVIGATION UNIT FLIGHT CONTROL COMPUTER RADAR/E-O DISPLAY HEAD-UP DISPLAY HUD ELECTRONICS RADAR/E-O ELECTRONICS RADAR FLUs			

* For calendar time from initial anniversary date

CONTRACTOR'S RESPONSE TO RIW DURING PROPOSALS

One of the biggest realizations for the weapon system contractor when he receives a Request for Proposal (RFP) that contains an RIW requirement is that the customer is asking him to delve into an area that historically he has not been directly involved in. That is, his responsibility is being extended to include operational or field performance with the major objective of demonstrating higher operational reliability and reduced support costs. In developing his proposal, the contractor looks to prior contracts and sees little precedence and historical information on this type of contract. Not withstanding, industry is fully aware of the dilemma the services are in - they are troubled with equipment having low reliability and high support cost and, at the same time, they are trying to reduce these problems with a new concept. Industry realizes that the services are taking a new approach toward improving the total support posture of a weapon system. This new approach is RIW, which, as a main ingredient, includes the involvement of the contractor and Government as a team, both with the identical aim - to reduce the rate of equipment removal and repair.

One of the most important elements in the building of the RIW response is that of properly pricing the warranty. All activities projected to be accomplished and all the major factors that influence these activities must be identified, analyzed, and converted into costs - costs that are projected far enough into the future to cover the time base of the contract. Items typical of those to be included are:

- Projected unit returns - failed units, good units
- Repair time/failed unit
- Test time/good unit
- Repair and test hour costs
- Material costs
- Asset control
- Test and repair equipment and facilities
- Data collection
- Engineering analysis
- Failure-rate improvement trend
- Modification costs
- Reporting to customer
- Direct labor rates
- Overhead costs
- Profit

The determination of the projected return rate and of the proposed guaranteed MTBF of warranted equipment are two of the most difficult parameters to quantify. In the F-16 contract, the avionics that were under consideration for the airplane were generally derivatives of avionics already in operational use or derivatives of avionics that had undergone some type of prototype testing. Since the return rate and operational MTBF were to be a function of the equipment in Air Force use, being handled and tested by Air Force personnel and controlled by Air Force data systems and asset control, the projected rates of return and MTBF were determined by use of Air Force data (e.g., AFM 66-1 data). The failure rates of same family and/or similar equipment were modified as a function of projected simplification, design changes, state-of the art improvements, environmental differences, etc., to derive estimates of the projected return rates and operational MTBFs for the F-16 program.

CONTRACTOR'S RESPONSE TO RIW DURING DEVELOPMENT

Contracts such as the F-16 contain the RIW provisions as options to be exercised during the development phase prior to production go-ahead or spares provisioning. The contractor's response during the development phase will be prompted by the timeliness and

sincerity of Air Force decisions and actions on RIW.

Prior to the Air Force exercising the RIW, the development contracts will by necessity be executed on the basis of traditional and conventional contract provisions. New weapon system contracts have a rigorous, formal reliability and maintainability program, which includes requirements for R&M design reviews, parts selection and screening, predictions, failure modes and effects analyses, and formal reliability testing of contractor-furnished avionics in the laboratory under environment during development and production phases. Under this traditional contracting method, if the RIW provisions are not involved, for all practical purposes the contractor's liability extends to delivery and acceptance of equipment.

On the basis of some studies that have been completed, it appears that to accomplish the objective of RIW, which is to improve reliability and reduce support costs, it would be most advantageous to exercise the RIW as early as possible during the development phase. These studies indicate that over 90% of the decisions that determine life cycle cost are made by the end of Full Scale Development. When the RIW options on a contract such as the F-16 are exercised, these options will be exercised before production go-ahead. This means that part of the design and development phase is still being accomplished. Once the RIW options are exercised on a contract, the contractor has a definite incentive to change his business-as-usual design methods to methods that investigate, identify, and reduce the number of potential removals and repair through design innovations.

Instead of trying to design the lowest-cost equipment that will meet engineering and reliability qualification, the contractor's objective will change to that of designing to the lowest cost per operate hour, which allows him to use more expensive materials and components in areas that will improve MTBF. If the contractor determines that a more rigorous and costly quality control effort on particular components would offer a significant improvement in MTBF and at the same time be cost-effective in terms of maximum number of equipment operate hours per dollar, he could and would institute such an effort.

Even the performance of all reliability program tasks would be influenced. For example, during the conventional contract reliability test, the contractor is vitally interested in the relevant failures that occur during the test. With RIW, emphasis is put on all failures that significantly influence return rates and guaranteed MTBF, and corrective action would be taken to preclude their occurrence in the field.

Under conventional contracting, engineering efforts associated with support problems are not well organized. With RIW, as a function of management necessity, engineering and design is thrust more directly and with full involvement into the arena of problem solving to improve the support aspects of the contractor's product.

During development flight testing, as the weapon system is being flown by both contractor and Air Force personnel, the contractor has his first opportunity to establish a tracking system on RIW units in an environment similar to Air Force operations. During this period, reliability and design engineers, coupled with quality control and logistic personnel, track the performance and problems of RIW units and evaluate asset and inventory control processes. Actual performance of RIW items during flight test are compared with those projected during contract negotiations to find problem areas and initiate corrective action as required. (Reference 2)

CONTRACTOR'S RESPONSE TO RIW DURING PRODUCTION

With the Air Force commitment to production go-ahead with RIW, the contractor is signaled to begin putting into effect the RIW provisions of the production contract. On contracts like the F-16, the contractor puts into effect the individual equipment subcontractor's RIW provisions.

Within a period of several months from contract go-ahead, the contractor submits a plan to the Air Force detailing the contents of two reports to be submitted to the Air Force - one covering RIW, the other covering RIW/MTBF:

- Under RIW, the Warranty Data Report is provided semi-annually. This report covers the warranty experience over a 6-month reporting period.
- Under RIW/MTBF, the MTBF Data Report is provided at the end of each measurement period. This report covers the information pertinent to the MTBF guarantee clause.

The contractor installs two items on each warranted unit prior to delivery: a seal to prevent unauthorized maintenance and a placard with the information that the unit is under warranty.

Test, repair, and modification facilities are activated to implement action on all returned units. Under RIW, certain activities are added to those performed under conventional overhaul contracts. Examples of some of these activities are as follows:

- o Engineering is involved in tear down, part replacement, and assembly. Engineering performs inspection and analysis of faulty parts to determine failure modes and of selected other parts to determine probable future failure modes.

- o Rigorous technical analyses are performed with fleet data on failed units and with in-house data from repair, overhaul, and test to determine changes that would decrease the return rate of units - changes in design, parts, quality control procedures, or overhaul procedures.

As design improvements are indicated as a result of field performance feedback and in-house evaluations, the improvements are made. Under conventional contracting these improvements would be delayed or never made because of the long process of paper work or of additional funding requirements.

Asset, configuration, and inventory control processes are implemented commensurate with the higher administrative and technical attention that is required under RIW contracting. These controls are vital to the operation of RIW. A piece of equipment that is sitting in a receiving area or delayed in the repair cycle or belatedly modified to the latest configuration is a detriment to the successful accomplishment of turnaround time within the specified time in the contract and within budgeted dollars.

A system of quantitatively tracking all parameters that critically influence RIW is implemented. Technical and administrative management must know the status of RIW, the problem areas, and the impact of proposed design or procedural changes on RIW performance so that comparisons can be made of actual performance versus required MTBFs, turnaround times, replacement response, etc. (Reference 2)

AIR FORCE-INDUSTRY STUDY KEY ISSUES

Since RIW is a new procurement process for the services and there is little precedence or historical data on this type of contracting, the Air Force is particularly interested in some elements of the implementations of RIW. This interest is centered about the proper application of some of the aspects of RIW so that RIW as contracted will be viable and will properly attain the objectives of improved reliability and reduced support costs. Some of the key issues requiring Air Force guidance that are being studied by the Air Force and industry are summarized below:

<u>MTBF Requirements</u>

- o Should the Government specify a minimum MTBF?

- o Should a joint Government/industry group review these requirements prior to RFP release?

- o Should the MTBF be as defined in MIL-STD-781B or should it be an operational value?

- o When should the MTBF requirement be applied and should it be related to growth or a point estimate value?

<u>Failures</u>

- o Is a failure defined as a removal for any cause or should there be exclusions? What exclusions should be taken?

- o How should turnaround time be defined and applied?

<u>Timing of RIW Application</u>

- o When and how should RIW be applied? (parallel development, competitive development, competitive production, options, tie to milestones)

- o How long should the duration of the warranty be?

RIW Contracting Basis

- What type of a contract should it be? (RDT&E phase with designed-in reliability, production with reliability and maintainability improvements)
- What type of an incentive structure should be applied?
- What should the reward-penalty relationship be?

CONCLUSIONS

Reliability Improvement Warranty contracting provides a new viable concept in fixed-price procurement, which, when executed, extends the contractor's responsibility for the performance of his equipment into the operational phase and can result in improved reliability and reduced supply cost. Reliability Improvement Warranty is now being applied on a trial basis and will require a new type of innovative management and technical administration of contracts — by the Air Force to assure attainment of the objectives of RIW and by the contractor to assure that reliability efforts do provide a reduced rate of returned units and result in the company meeting its RIW commitment at or less than the negotiated cost.

REFERENCES - FURTHER READING

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HIGH RELIABILITY DESIGN TECHNIQUES

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SUMMARY

Commonplace design techniques can be applied to a development program with the constraints of holding a normal cost ceiling and schedule, and these techniques can skillfully be controlled to provide higher reliability than would otherwise be expected. At the other extreme, special and unusual design techniques can greatly extend costs and schedule, but with proper application they can produce much higher reliability. This paper addresses the general situation between these two extremes, wherein a difficult reliability objective can be considered and techniques applied which will attain a preferred balance between reliability and all competing factors such as performance, cost, schedule, etc.

For this consideration much must be done before development contract award, including thorough understanding of the need for the desired reliability and the probability of its attainment under various trades and compromises. Agreement must be reached on the assignment of the first few functional models, the availability of sophisticated facilities for failure analysis, and the provision of close technical supervision of circuit design and analysis and mechanical layout. Preferred sources for all critical parts and materials must be both known and proven. It is the author's contention that adherence to the discussed techniques and their intent will generally lead to the attainment of optimum reliability prior to the need for a quantitative reliability verification test, and the question of reliability growth during the development program will be academic.

INTRODUCTION

Any of several different approaches might be selected and identified as special effort to design for high reliability. The level of effort will vary considerably among these choices and so probably will the results. At the minimum effort extreme management can put a ceiling on design costs and encourage any and all special design effort so long as it does not increase the cost or delay the schedule. With such limitations the most productive effort might well be to employ designers with the greatest successful background of design experience who valued their reputation for sound design. Then ensure that they are not assigned that which they feel they cannot accomplish. Frequently the need for high reliability is recognized to be worth an added increment of cost. Perhaps the greatest benefit then might be to encourage the design team to be more thorough and recheck its work with care, but all within the new somewhat increased budget and schedule.

This paper addresses the development program wherein specific high quantitative reliability is felt essential, and cost ceilings and schedule extensions are items for negotiation during which, if necessary, the quantitative level of required reliability is traded and compromised with other performance factors and with cost and schedule. Under these conditions it becomes important to review all those design techniques which show any promise of improving the reliability otherwise attained. In a given program then, those techniques which appear to have a high ratio of reliability yield to design effort can be adopted.

RELIABILITY REQUIREMENTS

Because of the essential nature of strong continuous motivation for the design team, the customer's need for reliability must be thoroughly understood. Just what drives his requirement? It may be life cycle cost. It may be a special importance of high product availability, or the penalizing cost of unavailability. Reliability may even be essential to the customer's economic survival. Quite likely it may have a specific relationship to the profits of his enterprise. And of course it may directly threaten the existence of his project. Reliability's role may be obscurely interwoven with maintainability, survivability, safety, or other contiguous specialties. An understanding of all relating factors is vital to optimizing trades between reliability and other performance criteria, and maintainability, producibility, schedule, cost, and production future.

With a valid understanding of the customer's need for reliability as a background, proposed contract commitments, explicit and inferred, which also identify related rewards, penalties, means for later adjustment and adjudication, and means for administering, judging, and policing can be considered, reviewed, and hopefully finalized into an efficient workable contract arrangement. Mundane as it may seem, the contract should make very clear what constitutes a failure relevant to reliability. Once a contract is in hand it becomes vital to identify exactly what contract statements specify reliability requirements, what contract verbiage must be judged to make further implication concerning reliability, and finally just what contract loop-holes permit exactly how much reliability flexibility. This total information should be both broadly disseminated and accurately understood by all members of the design team.

The entire development organization must be examined to verify the role that each member will play in order to achieve reliability objectives. It is essential that responsibility not only be assigned and accepted, but that the close relationship between design responsibility for achieving performance requirements and for achieving reliability requirements

(as well as those for maintainability, survivability, safety, etc.,) be recogn' ., be appreciated, and be efficiently functional. Furthermore, in an overall con' .ation, required reliability must be a basic objective of an authoritative member .. management in order to guarantee that attention that is vital to its achievement.

CONCEPTUAL DECISIONS AND RELIABILITY

Many conceptual decisions concerning the development of a new complex avionic product are made both consciously and subconsciously long before a customer is identified and long before commitments take shape. Many if not all of these early decisions affect reliability in a minor or often major way, affect the maximum quantitative reliability that is achievable within the state of the art, or within a practical limited extension of the state of the art. Unless quantitative reliability receives appropriate consideration, and unless this consideration is realistic for potential customers, much development time and expense may be lost before a satisfactory product emerges from the development process. Once conceptual decisions have been made, almost any change thereto is very painful because it becomes major redesign.

Typical conceptual decisions for our attention are the following. Analog electromechanical design may be supplanted with solid-state digital design. Should environmental control of avionics be achieved with hermeticity, with multi-stage cooling and heat exchangers, or with conductive cooling dependent on external environmental des'gn? Should the design be keyed to recently developed components where high confidence liability experience is still lacking, or to older less ideal components whose reliabi. .y is known? Designs keyed to components which do not have multiple sources for ready availability must be assessed for reliability risk against alternative design or means for avoidance if the supply pipeline shuts down for any reason during production.

Early conceptual decisions can often be made which provide later options for deciding approaches to reliability. However, during conceptual decision making someone has to keep at least an approximate running rough estimate of the reliability to be expected from each alternative.

RELIABILITY ACHIEVEMENT RISK

Before signing a contract for development with a customer who insists on a quantitative reliability requirement, some assessment of the probability of its achievement must be made. If the development will be chiefly limited to prior proven and well understood design concepts, then a total understanding of all performance aspects, all operating facets, of a closely similar design will provide the best estimating background. Especially valuable will be current exercising of a functional model. If such a background is impossible then all available laboratory data pertinent to the forthcoming design should be collected and studied in an attempt to equate theoretical design performance and laboratory observation. There is ever present a significant risk that total hardware functioning is not totally and completely understood and that laboratory data are not completely relatable to design values. In fact one frequently finds the latter portions of a design being accomplished experimentally on the laboratory work bench, even with cut and try techniques. Such omissions in theoretical understanding increase the risk of unexpected failure mechanisms and less than expected reliability. The desired tota. understanding becomes the basis for identifying the total performance requirements and the probable local environment for each piece part to be employed in the proposed design. In turn, reasonable reliability estimates can be calculated, required reliability apportioned as desired to concentrate expected difficulties in preferred circuits. Then the risk of insufficient reliability, or conversely probability of needed reliability achievement can be calculated.

During conceptual decision making, the manner of inserting quantitative reliability into the trade decisions requires that running estimates of probable reliability be maintained. When it comes time to assess the achievement risk, these estimates become the starting point, and they are updated with every bit of refined thinking that relates to total piece part performance, total local environment, and operational expectation. The selected piece parts with their refined estimates are compared to expectations from available (hopefully multiple) parts sources, and adjustments made in expected failure rates if necessary. From these failure rates are calculated reliability values for functional assemblies, units, equipments, and the overall system. End figures are compared with customer expectations, the latter is broken down to set an objective for each portion of the end product, in order that the allowable margin between expectation and requirement can become known. If there is little, or no, or a negative margin between expectation and requirement, then the requirement is so apportioned among the various units of the end product as to assign the greatest needs for reliability improvement to those places in the design where the expectation for improvement is judged greatest. When it is possible to go through this process before a contract is signed, final contract decision can take into account the expected risk of reliability accomplishment. Even if this risk assessment cannot be reached until after contract signing, it should still be made as soon as possible in order that the risk guide contract administration and later contract amendments.

Risk assessment can be a process of continuous refinement from the time of earliest design consideration. Rough reliability estimates based solely on approximate parts count are excellent as a start and have been described in the literature[1]. The degree of refinement thereafter is limited only by the degree of detail available concerning . rt useage.

ASSIGNMENT OF EARLY FUNCTIONAL DEVELOPMENT MODELS

Usually development contracts identify the disposition of all fabricated functional models of the end product. Accordingly, prior to finalizing a development contract, careful thought should be given to providing for reliability study in the assignment of early

functional models. Much experience seems to dictate that the first final configuration functioning unit off the production line should be assigned back to the development laboratory. This unit should be operationally scrutinized with utmost care to verify that every portion of every circuit properly functions exactly as expected for all variations of environment (electrical, and non-electrical, and in the total system) and for all modes of operation. If this is not so, then complete understanding must be achieved for the functioning observed and appropriate revision made to earlier theory so that expectations are then validated. This means that the laboratory must have a suitable environmental chamber, dedicated instrumentation, and replacement assemblies available as needed. With any degree of modern avionic system complexity, several months will elapse before unanswered questions concerning the new design begin to be worked out. Further, the crew assigned to this investigation must be rendered free from other priorities, and must have ready access to all portions of the development team in order to rapidly resolve misunderstandings and difficulties. Progress must be monitored on a daily basis, and management assistance provided for adequate support. Note that essentially all of the testing performed on this first unit should be verification of early subassembly development tests and their findings. Under no circumstance should large surprises because of enexpected difficulties at environmental extremes be expected. Obviously encountered failures should receive prime attention and this attention should not be relaxed until a complete understanding of the correct failure mechanism is acquired.

The second production model off the production line is usually demanded by the customer for form, fit, and function study. If this is so, then the third production unit (at the latest) should be assigned (for six months or more) to reliability assessment. Some care should be exercised with this unit to avoid introducing any failures non-relevant to reliability determination. An operating profile consistent with later official reliability verification should then be established. The prime objective of the testing exercise for this third unit is to 1) uncover design shortcomings and oversights pertinent to reliability; 2) identify workmanship problems and inspection difficulties; 3) spotlight parts selection shortcomings including omitted specification, insufficient inspectic inadequate source, and need for burn-in; 4) expose failure mechanisms of those failures which possibly will not be easily permanently eliminated; 5) provide indication of probable reliability variation among otherwise similar future production units; and 6) indicate the reliability and reliability variation to be expected for various options of design remedy. The progress made with this reliability test model may suggest great value for an option for assigning additional early models to reliability.

FAILURE MODE, EFFECT, AND CRITICALITY ANALYSIS, (FMECA)

Failure mode, effect, and criticality analyses have been amply described in a prior report[1]. Such analyses deserve mention at this point because it is important to begin them immediately after signing a development contract. Initial analysis effort should be based on considerations that went into conceptual design decisions and early reliability estimates, so that if errors in these estimates are to be uncovered, modifications can be considered at the earliest possible moment. These analyses should be made by those responsible for design in order that they recognize the effect of their design decisions on reliability. Assistance from reliability specialists is valuable provided the designer is not decoupled too far from the analysis. The FMECA should be revised and up-dated on a continuous basis as design details are resolved and as parts sources are identified and test data acquired.

PIECE PART PROCUREMENT

Inevitably every development will include a few or many long-lead-time procurement parts and components. Because of need for this long lead time, occasion will arise when subcontracts and purchase orders are placed immediately upon signing the development contract. Thus there is important early homework to accomplish in the procurement area in order to protect the achievement of high reliability against the pressure and sequence of tight development schedules.

A number of recommendations are to be made in this section for close scrutiny of piece part sources. Most of these recommendations apply regardless of whether the preferred source is a subsidiary of the developer's organization, even a contiguous department in his organization, or an unknown manufacturer. Given a choice, the best source is likely to be a stable organization with a long history in its product line, and a long history of very satisfactory procurement relationships for past development programs. In this ideal situation there is little need to study the source organization especially for the current procurement need. At the other extreme is the situation where the source organization has had no previous contact with the developer, and has not previously marketed (to any significant extent) the item to be procured.

Because more than a single source should be identified and verified for every procurement item going into a high reliability development program, all likely sources for the type of piece parts and materials customarily used in typical developments should be extensively surveyed prior to any specific procurement requirement. An adequate survey made by a team from the developer's organization should view and review the subcontractor or piece part manufacturer and his facilities with an experienced eye with respect to adequacy of design capability (versus state of the art), adequacy of quality control, reliability awareness, research background and design evaluation, permanency of optimum design techniques, production capability, cost and schedule performance, personnel stability and longevity, labor relations, and financial solvency. While these criteria may seem remote from reliability, any interuption in procurement during production leads to substitutions and the need to re-evaluate the reliability of the developed product. Prospective sources for piece parts who rate highly in the survey but have not previously supplied the developer should be given trial procurements for at least partial verification of the survey findings.

History contains many instances of reliability difficulties that have arisen and then been traced to lack of tight control of a procured piece part. No specification, practically speaking, will spell out in detail every characteristic vital to a complex system. Actually procurement specifications with special language specify certain critical parameters. Other parameters are covered by standard specification practice (fine print). Still other factors are implied by customary procurement practice. And finally, inevitably a few factors, nowhere specified, are established by habit or the custom of the piece part manufacturer. This looseness of specification is usually found at every level of procurement. Thus the piece part manufacturer has only semi-complete control over the sources of his raw material. He may be forced to change sources and in all good conscience establish to his own satisfaction that his new source provides everything needed and previously provided by the old source. Surprisingly these substitutions often lead to difficulties and all concerned then learn of unknown dependence on unspecified parameters.

Standardization of piece parts to be employed in development while never completely inclusive is a great asset for source selection philosophy. For instance, proper control of procurement of high reliability parts nearly always requires a specification and special drawing by the procuring developer in order to not only specify any parameters overlooked by a standard specification, but to identify precise acceptance inspection requirements (in terms of both source's and developer's test and inspection facilities) and statistical acceptance plans if acceptable, reliability evaluation requirements, basis for rejection and return for credit, constraints on material substitution, burn-in if any and other special screening.

CIRCUIT DESIGN

At the top of the list of high reliability considerations for circuit design is the need for a standard parts list (SPL) or handbook and a rigorous authoritative organization for its control. While the gradual acquisition of preferred parts for inclusion in the SPL, based on successful experience, is perhaps the most painless means for the creation of an adequate SPL, other short-cut means have been quite effective. One such means is the following.

With appropriate anticipatory language in subcontracts and purchase orders, a Parts Control Board (PCB) composed of a chairman from the developer's organization, and a parts specialist (member) from each significant supplier is organized and begins its meetings on a frequent (monthly) schedule immediately upon award of the development contract. The PCB by majority vote, but with the chairman's power of veto, agrees on a preliminary SPL that is to govern all suppliers. Any additions (and deletions) to the SPL are made subject to discussion and vote by the PCB. Any and all piece parts to be used by the developer or any subcontractor must either be placed in the SPL, or be specifically approved by the PCB for the singular use and effectivity upon which the vote is taken. Often special verification tests are demanded, and later experience may then warrant inclusion in the SPL. The collective experience and intelligence brought together by the PCB leads rapidly to a practical SPL. The frequency of PCB meetings is adjusted to needs and early reduction in meeting frequency is expected. The desirability for special drawings, special tests, and acquisition of special data can be reviewed by all and discussed. Above all, the parts sources then readily recognize the pervasive importance of reliability in the mind of the developer.

The next most important consideration for high reliability circuit design is circuit analysis. In this computer age much has been done toward standardized computer analysis of electronic circuits. Initially, it is well to note that if there is to be anything like an extensive investigation of an electronic circuit, a design which minimizes the number of different types of circuits (maximizing the repetitive employment of a minimum number of circuits) will both ease the analysis burden and increase the likelihood of total evaluation of the circuits used. The design of large scale digital computers has been a classic example of an extremely complex large system which employs an amazingly large quantity of but a few different circuits.

Computerized circuit analysis begins with the creation of an accurate equivalent circuit. The value of all subsequent results will be heavily dependent upon the assumptions employed in claiming accuracy for the equivalent circuit used. The writing of circuit equations to cover circuit performance in terms of parts parameters can benefit today from the increasing emphasis on mathematics brought about by the computer age. The circuit equations will usually incorporate into one or another of various existing general computer programs, which can then be debugged, run, and the computer output analyzed.

Because programmed circuit analysis by computer requires as inputs various voltages, values of resistors, capacitors, parameters for transistors and integrated circuits, and the like, it is convenient to introduce therein initial tolerances, value variations with temperature, humidity, and life, and all the drift and aging factors that affect proper functioning of the circuit.

Worst case analysis is made when all circuit parameter values for computer input are simultaneously chosen at those tolerance and drift extremes that abridge proper operation the most. Worst case design is achieved if desired functioning prevails with such extremes of parameter values. Obviously the frequency with which a repetitive circuit configuration is repeatedly employed in an overall system can provide strong influence in the direction of worst case design.

Studies have been made wherein the statistical distribution of tolerances is considered so that calculation of the probability of proper operation can be made for something less than worst case design. However, it is usually found that with highly replicated circuits,

the savings in circuitry, space, weight, power requirement, and cost is minor for statistical design over worst case design when compared with the rapid drop in reliability. The great advantage of worst case design (other than its greater reliability) is that it can be performed with a minimum of parameter design information, and it avoids need for assumptions or voluminous data for the assignment of statistical distributions to the tolerances and drifts. In any case, the opportunity to explore circuit function as parameters are varied through use of a programmed computer, can provide tremendous insight toward effective total understanding of the design of high reliability circuits and thus high reliability avionics.

The need for useful tolerances for the parameters of piece parts is easily accommodated for parts that have been in regular high volume use and procured from steady sources. On the other hand, new items, or significant changes to old items can raise new questions as to expected tolerances. While collection of quantities of measurement and test data, painful as it may be, is undeniably most valuable, a first hand understanding of the part manufacturer's production process, in detail, and especially if it is highly mechanized, can permit the specialist to make quite useful assumptions as to tolerances, with at most, abbreviated test and measurement of selected parameters on small samples.

If second and third sources for various piece parts exhibit parameter tolerances or drift behavior markedly different than the preferred source, the computer analysis program can quickly evaluate the effect on circuit performance, and thus verify the adequacy (or inadequacy) of selected alternate sources, and possible remedy.

LAYOUT DEVELOPMENT

The remarkable progress in solid state development of large scale and medium scale integration has the effect of compressing more and more avionic complexity into smaller and smaller volume. The lower power requirement of solid state active circuit elements no longer protects the designer against cooling problems. Means, and preferably skillful efficient means, for heat removal must be considered from the very beginning of conceptual design, and attention to this dare not be relaxed until hardware models permit valid measurements of temperatures and thermal gradients under all possible conditions. Unmistakable evidence as to the adequacy of cooling must be developed.

The cooling problem must be addressed not only for system operation in the intended application, but also for operation during all levels of maintenance, for accidental unintended operation in conjunction with other repairs, and for emergency checking. The cooling problem must be considered for all possible environments from tropical summer to arctic winter (if that deployment is possible). If cooling under some conditions such as during maintenance force dependence on auxilliary units (viz., portable refrigeration units), the reliability of these auxilliary units must be sufficient.

If cooling is by air flow, then extremes of air density, flow rate, humidity, thermal gradient, and carried contamination must all be considered. Air flow cooling raises the need for a decision on what portions of the design to make hermetic to protect against contamination. If cooling is by a liquid refrigerant, can all the important thermal gradients between the cooling liquid and the most distant sensitive piece part be adeeuately estimated? Are those temperature tolerances essential for proper effectiveness of the cooling air or liquit really practical? Can they be adequately estimated for all conditions of operation of the system?

Mathematical computation of heat flow is complex but extremely valuable if the needed parameters are known. The thermodynamics involved with dense avionics becomes so sophisticated, that a successful design is only considered achieved after thorough laboratory measurement of an extremely accurate and representative operational model. Accordingly, hardware models of proposed cooling designs are often the earliest items for model shop fabrication, and adequate environmental test facilities for such models often see continuous assignment to cooling problems from beginning to end of the contract.

Many reliability problems have arisen because a new design was not properly evaluated during non-operating exposure to low temperature extremes. Failure mechanisms related to thermal expansion and contraction and the rate of expansion and contraction are too often overlooked. The mechanical effect of start-up after extended cold-soak can easily be observed once the hardware exists, but difficulties found so late in the development program are usually most inconveniently dealt with.

Susceptability to shock and vibration usually is controlled in large part by the designer's past experience. However, with the expansion of other horizons, has come expansion of the shock and vibration spectrum that can sometimes be encountered. Specialists in shock and vibration, if they are given the opportunity, time, and funds to design suitably representative testing fixtures, and if they have necessary laboratory exciters and sensors, can do quite well in evaluating system performance in a shock and vibration environment. Again, by the time such evaluation can occur, development progress is far beyong the convenient point for structural remedy. The answer is to investigate mechanical design early through simulation and simplified models, to augment past experience to the extent necessary.

FAILURE ANALYSIS

Laboratory facilities adaptable to the study of any type of system failure should be established close by the development laboratory. These facilities should then be employed to establish or verify the physics of failure in every instance of observed failure where such understanding does not positively exist. It is only with recognition of the detailed failure mechanism that decision can be made as to the value to reliability of its elimination. Because many of the clues needed for effective failure analysis exist only at the

point of failure, and in the minds of those observing the failure, it is essential that the development team operate cooperatively in the failure analysis process. It is usually of little benefit to send a failed item back to its manufacturer for failure analysis, in large part because the motivation is wrongly directed then. If warranties become obstacles, then arrange to invite those responsible to come to the failure analysis laboratory that is adjacent to the site of failure and to actively perform the analysis there (rather than in their own facility) in collaboration with the development team.

Industrial experience has shown that an effective failure analysis laboratory must include or have local access to facilities for radiographic/x-ray study, microscopy, photography, chemical analysis, and complete electrical and mechanical measurement in white room environment. Appropriate funding must exist, because failures cannot be selectively analyzed to fit a limited budget. Useful analyses leading to a useful report of conclusions average between twenty and one hundred manhours each.

While it is quite customary, it is still important to mention the necessity to keep thorough data files of observed failures, from the very beginning of development onward. Many schemes for achieving this by computerized methods have been described. The principle value is to 1) quickly recover past data on similar or apparently similar failures and failure mechanisms, and 2) to develop at least a rough index of the reliability or comparative reliability to be expected for the failed item.

MANAGING HIGH RELIABILITY DESIGN

Perhaps the most typical method for management's control of a development program is via design reviews. Before discussing design reviews, let us look at possible means for the leaders of the development team (rather than non-technical management) to keep themselves up to date and to properly advise lower echelon members of their team.

Parts application data sheets can be designed to keep running account of essentially all important application information (including derating) for every piece part to enter design consideration. Typical data sheets have already been described[1]. These data sheets at first glance may seem to constitute considerable extra work for a circuit designer. However, on closer inspection it will be found that essentially all the data for entry are data that the designer already must possess if he is to make a favorable decision on the use of a particular piece part. The data sheet just conveniently collects in one location on a routine format these data otherwise often existing only in the designer's notebook, or only in his head, and sometimes given a proprietary cloak of secrecy by him until he can verify the wisdom of his choice. When such parts application data sheets are routinely kept by all circuit designers, and kept up to date, supervisory design personnel can review them on as frequent a basis as seems necessary without tying up the circuit designer with questions. Concurrently, those with responsibility for reliability can also review the application data sheets, and therefrom make preliminary calculations to indicate trends and expected problems.

Design reviews for the benefit of supervisory design personnel (and not higher management) should be held periodically and frequently. Care has to be taken with respect to those invited to be the audience, and with respect to those invited to offer critiques and criticisms, to make sure the responsible designer does not withhold early considerations for fear of criticism or of appearing to exhibit stupidity. A true team atmosphere rather than encouraged competition among designers will go further to yield high reliability. Homework should be assigned in advance of a design review so that other unrelated impartial designers without conflict of interest can study to their own satisfaction those portions of a design judged ready to release (or under criticism for some difficulty), and then report their findings or conclusions at the design review. It is important to realize that design reviews are not an element of the reliability program, but rather a tool for technical management for sound overall technical design, and any reliability improvement that results is because of the soundness of the resulting design rather than because of what took place in a design review.

Because upper, non-technical management, as well as customer personnel usually have interest in the design review as a means for monitoring design progress, it is customary to identify a specific limited number of full dress design reviews, to be held at particular program mileposts, and to open these reviews to all interested. With proper planning, the design team can pre-insure at least to a large extent, the favorable presentations that will be made in these formal design reviews, and can use their own more frequent informal closed reviews to provide opportunity for dress rehearsal.

FIRST ENGINEERING MODELS

As the design approaches the point where first models can be ordered from the model shop, the design should be closely reviewed by inspection and quality control specialists, as well as those responsible for fabrication methods. Not only must it be possible to fabricate a model that satisfies the designer with respect to its representation of his design intentions, but it must also be possible to efficiently inspect the materials and parts going into the fabrication, as well as the assembly process as it takes place. Many designs have so buried early assembly operations under later assembly that when questionable performance raises doubts as to proper fabrication, disassembly is required to verify.

Prior to the arrival of solid state electronics, it was often possible to breadboard early design considerations so that most all questions were answered and decisions made before fabrication of a model that represented the mechanical design. While breadboarding still exists, there is an ever increasing chasm between breadboard performance and the performance of a representative engineering model. Thus, while some indication of design

adequacy can be gained from a breadboard model, and more from a brassboard model, design adequacy for reliability assessment has little value prior to the existence of a truly representative engineering model of the design as it is expected to be released for production tooling. In fact reliability verification can usually be questioned unless it takes place on a unit fabricated from production tooling.

The need for a near final model for reliability assessment and the possible magnitude of design change that may result from anything less than satisfactory assessment defines a classic conflict that confronts the designer. To minimize possible criticism, and added expense and delay incurred by reliability problems, it behooves the designer to favor sound design and high reliability as much as is humanly possible in every early decision he makes. During the many early verification steps he takes prior to the existence of representative final hardware, he should carefully explore every anomaly, every situation where his observation does not agree with his expectation. No hasty hypotheses should be used to get on with development rather than study an unexpected observation. The end result of this technique is to minimize more and more the surprises encountered. In fact, with detailed and extensive application of these principles, the performance of a verification test should engender no concern to the designer.

CONCLUSIONS

The approach to high reliability design described herewith attempts to identify high reliability as an inherent element of sound comprehensive thorough design. It is the author's experience that such an approach leads to the desired level of reliability far more rapidly and with less expense than an approach where difficulties caused by design short cuts and oversights, leading to observable failures, are eliminated one by one as failure observation identifies each problem. For one thing, the fail and fix approach eliminates (but not very rapidly) the frequently repeating failure mechanisms, but provides little assistance for the elimination of infrequent failure mechanisms. In today's complex systems, it is easy to find literally thousands of different failure mechanisms none of which are repeaters often enough to permit elimination, but which in total produce many all different failures with attendant low reliability that does not respond to customary reliability growth techniques.

The designer who knows every facet of all his parts and materials, completely understands the total functioning of the circuitry he designs and its every limitation (and the reasons therefor) to obtainable performance, when allowed and motivated to produce a careful design will obtain state of the art reliability in minimum time and expense.

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Design of Electronic Circuits and Component Selection for High Reliability

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ABSTRACT

For high reliability applications rules are given for the selection of components. Determining the suitable technology, part derating factors and then the selection or writing of specifications for parts procurement are described. The necessity of precap visual inspection and screening of components as well as incoming inspection by the user for high reliability applications is emphasised. The use of plastic IC's for HI-REL applications and a new development in this field is discussed.

The second part is concerned with the design of reliable circuits. Precautions to be taken against voltage and current overstressing and the selection of the proper supply voltage are described. The use of MSI and LSI and synchronous operation is suggested to increase the reliability. Noise immunity and its influence on reliable operation is discussed. Finally redundancy versus screening and the cost of reliability are considered.

1. INTRODUCTION

The first thing to do in the design of an electronic circuit is to establish the requirements of the mission and the anticipated environments. Then one can define the components compatible with the circuit parameters and the environment. In the following guide lines are presented which are intended to help in the selection of components for high reliability applications. In a second part circuit design rules for reliable operation are given based on problems which are frequently encountered. Some basic principles important for reliable circuit operation are presented with emphasis on active semiconductors because most of the problems encountered are connected with these.

2. COMPONENT SELECTION

2.1. CHOOSING THE RIGHT TECHNOLOGY

For the selection of a suitable technology one has to know the requirements of the application and the environmental conditions first. Table I gives for instance the standby power dissipation of several families of IC's. Fig. 1 gives the dependence of the power dissipation on the operating frequency and also the maximum frequency of operation for these IC's. One has to take care that both in the power dissipation and the maximum operating frequencies including aging and component tolerances there is still enough safety margin that the application can be implemented. This will be discussed in more detail in the paragraph on part derating factors.

Table I: Standby Power for Several Technologies

Digital Logic Type	Standby Power Drain / Gate
CMOS	1 µW
PMOS (Static)	0,5 mW
PMOS (Dynamic)	50 µW
DTL	4mW
TTL (54 series)	10mW
ECL (10 K series)	25mW

Most important then is to choose a technology the reliability of which has been proven. This can be verified by using Mil Standard or space-qualified components. It can for new devices also be done by performing life-time tests oneself and by evaluating the quality of the components to be used by the means of destructive physical analysis as will be described in the paper on Reliability Testing of Electronic Parts. In any case however it is most important to procure the parts to definite specifications.

2.2. WRITING AND SELECTING SPECIFICATIONS

If possible parts should be procured to already existing Hi-REL specifications such as MIL-Specifications, GfW or RAE specifications. This simplifies the procurement of parts because the manufacturer already has test facilities and programs ready.

If a part shall be procured to a new specification, the user should negotiate with the manufacturer, sometimes a minor change can result in a considerable price and/or lead-time advantage. For mission critical parts SEM quality evaluations on samples of one lot may be required [1] . All the inspections and tests done by the manufacturer must be performed to documented procedures. Included in the specs should for critical parts be the pre-cap visual inspections by an independent inspector after the component manufacturer has completed his inspections (see below). Also the witnessing of a critical parameter test may be called for.

In MOS and linear devices a test of the input protection system may be necessary because as will be shown a lot of failures are due to electrical overstressing at the input. The specified burn-in time varies very much between specifications. Some specification systems call for double delta measurements, for relays sometimes an ultrasonic foreign particle monitoring procedure is specified. All this has a drastic influence on the price of the devices, so one should really take good care in the definition or selection of specifications.

Table II and III show the tests called for by GfW, MIL STD and MSFC 85 MO specs for transistors and IC's, respectively [2] .

Table II: Screening Tests for Transistors and Diodes to be made in Several Specification Systems

Requirements	Specification System				
	GfW			JANTXV	MSFC 85 MO
	A	B	C		
Lot identification	x	x	x	x	x
Internal visual	x	x	x	x	x
Serialization	x	x			x
High Temp. Storage	48	48	48	48 & 24	
Temperature Cycling	x	x	x	x	x
Thermal shock	x	x	x		
Acceleration	x	x	x	x	x
Mechanical shock	x	x	x		
Leak test	x	x	x	x	x
Burn in	500	168	168	168	240
Double drift Δ	x				
Drift Δ		x		x	x
High Temp. Reverse Bias	PNP and JFET Transistors only			x	x
High/Low Temperature Measurements	Sample	Sample	Sample	Sample	
PDA (Percentage Defects Allowed)	5%	5%	5%	10%	-

Table III: Screening Tests for IC's to be made in Several Specification Systems

Requirements	Specification			System	
	GfW			CLASS A	MFSC
	A	B	C	883	85 MO
Lot identification	x	x	x	x	x
Internal visual	x	x	x	x	x
Serialization	x	x		x	x
High Temp.	48	48	48	24	24
Temp. Cycling	10Cy	10Cy	10Cy	10Cy	10Cy
Thermal shock	x	x	x	x	x
Acceleration	x	x	x	x	x
Mech. shock	x	x	x	x	x
Leak test	x	x	x	x	x
X-RAY INSP.	x			x	x
BURN-In	500	168	168	240	240
Double Drift Δ	x				
Drift Δ		x		x	x
High Temp. Rev. Bias	x	x	x	x	
High/Low Temp. Meas.	x	x	x	x	x
PDA Electr.	10%	10%	10%	5%	
Other	5%	5%	5%	5%	
SEM				x	x

GE Nimbus and the international MAROTS Specifications for instance also call for SEM inspection of Microwave Transistors.

As one can see in the tables the specification calls for rejection of a whole lot as the Percentage of Defects Allowed (PDA) is exceeded. This PDA limits are different for particular components, for transistors they vary from 5-10% whereas resistors have PDA limits from 3-5%. If exceeding of PDA limits is considered as absolute rejection criterion this can have dramatic influence on costs and delivery times. General Electric [2] reports that if the amount of rejects is within 50% of the specified PDA then by some retesting and categorization of defects 6% of the lots otherwise rejected can still be saved.

2.3. PART DERATING FACTORS

The part selected for a specific high reliability application must be chosen so that it will not be operated at or near its maximum specified rating. For reliable operation the part has to be derated. For individual components the stress to be derated is different. In the case of semiconductors it mostly is the power to keep the temperature down, whereas in capacitors it is the voltage stress on the dielectric which is most critical. In the case of relays or for r.f. transistors which are operating at very high current densities the current must be derated. Table IV gives some part derating factors which are generally agreed on [2] . For semiconductor devices a maximum junction temperature of 125°C should not be exceeded.

Table IV: Part Derating Factors

Part Type	Parameter to be derated	Derate to percentage of maximum ratings
DIODE	POWER	20-50%
TRANSISTOR	POWER	15-50%
IC-Digital	FAN-OUT	40-80%
IC-LINEAR	CURRENT	85%
THERMISTOR	POWER	50%
CAPACITOR	VOLTAGE	30-70%
RESISTOR	POWER	20-50%
TRANSFORMER	TEMPERATURE	$25^{o}C-30^{o}C$
INDUCTOR	TEMPERATURE	$25^{o}C-30^{o}C$
RELAY	CONTACT CURRENT	50%
CONNECTOR	CURRENT	50-70%
FUSE	CURRENT	20-50%

2.4. EFFECT OF PRECAP VISUAL INSPECTION ON THE RELIABILITY OF IC's

For everyone who has ever performed failure analysis of IC's it is striking how many of the failures (even of High-Rel devices) can be traced to causes which could have been detected by a proper visual inspection.

Failures detectable by means of an optical microscope include:
. Oxide defects (indicated by different color)
. Metalization defects (voids, scratches, bridging, corrosion)
. Mask misalignment
. Cracked dice
. Poor bonds (misplaced, bad wire dressing, double bonds)
. Poor die bonds.

Fig. 2 shows a double bond on a post which is cause for a reject because the tail might come off. There is a strong tendency to use precap SEM inspection for the detection of possible metalization defects in mission optical parts. Fig. 3 shows a metalization discontinuity at a window in the oxide which can only be detected in a SEM. Specifications for SEM inspection are available [1] . It has been shown [2] that even after the manufacturer's precap visual inspection as much as 3,7% of IC's have still had to be rejected by a customer inspector. This stresses the need for visual inspection of critical parts and also the presence of an inspector at the manufacturer at the time the parts are manufactured.

2.5. SCREENING OF COMPONENTS

The basic philosophy of screening is that potential failures are detected by means of testing. Testing may include the application of certain stresses which will cause weak devices to fail, but will not weaken good units. The amount of stress applied and the kind of tests performed during screening has to be determined for each specific part. For different technologies different stress must be used. For plastic devices other tests have to be used than for hermetic ones and for ceramic packages some stresses cannot be used that are good for metal case.

The major causes of failures in IC's are given in Table V for bipolar and MOS IC's, respectively. It is also indicated in the table by which screen this failure

mechanism can be detected. The statistics are from two sources [3 bipolar] and [4 MOS] and some of the failures in one source are not distinguished in the other. But it can be clearly seen that surface problems and electrical overstress prevail in the MOS technology and so specific screens for this failure mechanism have to be used.

Table V: Statistics of Major Causes of Failure

Type of Failure	Percentage in bipolar technology	Percentage in MOS technology	Screen used for determination of weak IC
Wire bond	33%	5%	Vibration, mechanical shock, thermal cycling
Metalization	26%	23%	Thermal cycling, measurements at l[illegible] temperature, preca[illegible] SEM inspection
Photolithography	18%	not distinguished	[illegible] visual
Surface problems	7%	38	Power or high Temperature Rev. Bias (HTRB) burn-in
Package defects	10%	8%	Visual inspection, leak tests
Parameterdrift	not distinguished	7,5%	Burn-in either power or HTRB
Electrical overstress	"	10%	Test of input protection circuit on sample basis
Miscellaneous	6%	8,1%	

The cost of screening is given in an RAC publication [3] . For MIL Std 883 C[illegible]s A devices the bids for the whole spectrum of tests ranged from $2.60 to $7.90. For Class B devices it ranged from $1.36 to $4.75.

Especially important during the screening of components is parameter drift. The established limits of parameter drift drastically influence reliability but also the cost of parts. Typical values for the maximum allowable parameter drift published by GE [2] are given in Table VI.

Table VI: Maximum Allowable Parameter Drift

Part Type	Parameter	Maximum Allowable Drift from the initial value
Transistors	Gain (H_{FE})	+20%
	leakage I_{CBO}	±100% or 10 µA whichever is greater
FET's	Transconductance	+20%
Signal Diodes	Leakage I_R	±100% or 10 µA
	forward voltage V_F	±10%
Zener Diodes	Leakage I_R	+100% or 50 µA
	breakdown voltage	±2% of initial
Digital IC (TTL)	V_{OH}	±10%
	V_{OL}	±20%
	J_{IL}	±10%
	I_{IH}	±10% or 4 µA
Film Resistors	Resistance	±0,2% + 0,01
Wirewound Resistors	Resistance	±0,2% + 0,05
Capacitors	Capacitance	
Ceramic		±10%
Glass		±2%
Plastic		±5%
Thermistors	Zero Power Resistance	±1%

2.6. INCOMING INSPECTION AND SCREENING BY THE USER

That even after all the screening performed by the manufacturer of a component an incoming inspection by the user is necessary has been often stressed. We have once had the case of a space qualified component stamped as a digital IC which actually had a linear device inside the package. Recently published data also indicate this need. Table VII shows the information that Goddard Space Flight Center has published [5], indicating that after incoming inspection and additional screening even for JANTX transistors the rejection rates were as high as 20%.

Table VII: Incoming Inspection and Screening Rejection Rates

Type of transistor	Screening Test Rejection Rates in %
JANTX	20.3
[illegible]	34.4
COMMERCIAL	63.8

So for mission critical parts (and preferably for all others too) there should be an incoming inspection and as the Goddard report has shown also some limited amount of additional screening.

2.7. USE OF PLASTIC IC's

There has been a lot of discussion on the use of plastic IC's for Hi-Rel applications [6]. A new development by RCA shows good promise of overcoming the major problem encountered in all plastic IC's namely that of hermeticity (see fig. 4). A passivation layer of silicon nitride is used to protect the silicon surface. The junctions are contacted by means of a platinum-silicide contact. Then a three metalization consisting of Ti-Pt-Au is used with Ti used for good adherence, Pt as a diffusion barrier between the gold and the titanium and Au for good conductivity. On top of the metalization there is another passivation layer consisting of phosphosilicate glass. Fig. 5 shows the Weibull Probability Chart for standard Motorola C-MOS plastic devices [7]. After a little more than $2 \cdot 10^3$ hours 50% of the devices have failed in 85°C/85% R.H. environment with a bias of 10 V. Also indicated are the results of the same test on the RCA TRIMETAL Plastic IC's [8] which show no failure even after $5 \cdot 10^3$ hours of operation. But up to now only few types of IC's are available in the new technology.

3. DESIGN OF RELIABLE ELECTRONIC CIRCUITS

3.1. HANDLING OF INTEGRATED CIRCUTS AND STATIC OVERVOLTAGE PROTECTION

In failure analysis statistics it has been determined that the failures due to mishandling of the devices is in the range of 10% [4]. Especially sensitive to mishandling are MOS IC's but also bipolar linear IC's (especially with high input impedances or circuits with low output impedances are in danger [9]. Besides overstressing by exceeding the rated values during tests and in operation, the device might be inserted in a wrong way. Most frequent however are defects by excessive static voltage at the input of MOS devices with insufficient protection. Fig. 6 shows a typical input protection circuit for C-MOS devices. Fig. 7 shows the implementation on an IC.

Table VIII shows GSFC results of failure analysis on C-MOS devices [10]. The failure mode of 44 % of the total amount of failed devices was electrical overstress.

Table VIII: GSFC Results of Failure Analysis of C-MOS

Failure Mode	Number Failed	Percent Failures
electrical overstress	63	44.7
contamination	19	13.5
gate oxide defect	18	12.8
not defective	17	12.1
open or discontinuous metalization oxide steps	6	4.3
*radiation damage	4	2.8
not determined	3	2.1
mislabeled	3	2.1
hole in field oxide	3	2.1
smeared or scratched metalization	2	1.4
defective bonds	1	.7
cracks in die	1	.7
mechanical overstress	1	.7
	141	100%

*purposely exposed to radiation

For High Reliability applications certain handling precautions must be taken:

- MOS devices and high impedance linears should be shipped with leads shortened
- The surfaces of working benches, chairs and handling equipment as well as the operator should be grounded
- Control humidity to no less than 50 % R.H.
- Clothing should resist static charge build-up
- Avoid power transients (no insertion or removal of circuits with power on)
- Soldering irons are to be grounded and temperature controlled ones checked for spikes during temp. control
- Ground unused inputs
- Check power supplies and testers whether they have a voltage spike as the mains is switched off or during power failure. This is especially important for burn-in racks (use crowbars if possible)

Besides the measures described above it is very important that in the design of circuits care should be taken to avoid overstressing. For instance, due to the particular protection circuits, very high currents can flow if the power supply of C-MOS circuits is switched off and a low impedance source is still connected to the input of that circuit. In this event the high current will flow through the protection diodes and can lead to damage of these. So whenever this can happen a resistor limiting the current to a safe value has to be added. Especially in multiplexers, where external sensors are still connected, this kind of failure is quite frequent. Also additional capacitors after this limiting resistor are sometimes advisable to integrate voltage spikes on long wires from sensors to the electronic package (as frequently found in airplanes) if the speed allows it. Some of the C-MOS devices oscillate if inputs are left open, because the complementary output transistors float through the active region of their characteristic. So unused inputs must be grounded and even the inputs of the IC's on each printed circuit board would best be grounded by a high impedance resistor because during servicing the previous card might be removed and the inputs would be floating.

3.2. PRECAUTIONS FOR OPERATION OF INTEGRATED CIRCUITS AT HIGH CURRENT LEVELS

Most of the high current drivers in both, bipolar and also MOS technologies, are not short circuit-proof. Care has to be taken not to exceed the specified values. Fig. 8 shows a metalization burn-out as a consequence of too much current in a C-MOS device. Three devices were connected in parallel and when one transistor metalization opened up the other two metalizations also burned out. In C-MOS and TTL integrated circuits current spiking occurs which can reach quite high levels of current. During switching between states there is a period where both transistors connected in series across the power supply are conducting. For the case of C-MOS circuits this is shown in Fig. 9, which gives the current drain of a CD4001 depending on the input voltage. For a supply voltage, which is higher than the sum of the threshold voltages of the two transistors, there is considerable current across the transistors. Therefore the power supply voltage should be properly chosen such as not to exceed critical current levels. Fig. 10 shows the dependence of the power dissipation of C-MOS circuits on the rise and fall time of the input pulses and the supply voltage for a fixed pulse repetition rate of 100 Kc. It can be seen that above a certain value of rise time the power dissipation increases quite strongly. This increase in power dissipation has to be taken into account if, due to aging or radiation damage, the threshold voltages and therefore the switching times increase.

Another problem encountered in IC's is that of PNPN latch-up. It has been reported [11] that a number of C-MOS circuits of the CD4009, CD4010 type had been destroyed by PNPN latch-up. Every IC with an isolation diffusion shows a PNPN structure and if the number of current carriers in the IC is high enough, then the device will latch on like an SCR. Due to the lack of current limiting resistors this will lead to the destruction of the device. So care must be taken to avoid too high output currents. No PNPN latch-up occurs for the CD4009/10 if $U_{DD} < 10$ V and $C_L < 200$ pF.

3.3. SELECTION OF PROPER SUPPLY VOLTAGE

In most technologies the supply voltage to be used is fixed. In technologies such as MOS and C-MOS however, the supply voltage can in some instances be chosen over a very wide range of 3 V to 18 V. The supply voltage first influences the speed of operation. Fig. 11 shows the dependence of the rise and fall times of the output pulses on the supply voltage for the IC CD4001 for a capacitive load of $C_L = 50$ pF. The output impedance also depends on the supply voltage as shown in Fig. 12. The AC and DC impedance decrease with increasing supply voltage. As lateron shown, the noise immunity also increases with the supply voltage. It would therefore seem that it is best to operate near the maximum specified voltage. There are some drawbacks however. First as already described above (see Fig. 10) the power dissipation increases with the supply voltage.

A much more important problem is however illustrated in Table IX which is based on the results of Motorola [12] and SSS [13] voltage stress lifetime tests at several supply voltages. It is seen that Motorola units show a failure rate at 18 V, which is higher by a factor of 16 than that at 10 V. The factor is still 13 between operation at 10 V and 15 V. Similar measurements by SSS show a failure rate which at 15 V is three times higher than that at 10 V. Therefore, in order to keep the failure rate low, a compromise between increase of speed and the need for reliability has to be made.

Table IX: Influence of Voltage Stress on Failure Rate

[illegible]

3.4. IMPACT OF MSI AND LSI ON SYSTEM RELIABILITY

The failure rate for SSI and MSI circuits is basically the same and so because of the much higher number of equivalent gate functions, the failure rate per gate is lower. Table X illustrates this for a typical case.

Table X: Respective Approximate Failure Rates of SSI and MSI

	failure rate / IC at 55 °C in % / 1000 h	Complexity number of equiv. gate function	failure rate/gate at 55 °C in % / 1000 h
S S I	0,010	5	0,002
M S I	0,015	50	0,0003
		Ratio	~ 7

So either the same problem can be solved more reliably or considerably more complex problems can be solved at the same reliability.

With the availability of single chip LSI microprocessors a new era of circuit design has arrived. It is no longer necessary to implement different circuits for control, computation or experiments in always changing hardware designs. Using a microprocessor it is only necessary to change the software and use different read-only-memories and perhaps some additional analog-to-digital or digital-to-analog converters. With the possible use of the same circuit for different applications this minimizes the amount of different parts and thus increases the reliability. Besides the experience with previous designs, using the very same IC can be fully utilized. In addition the high complexity LSI circuit of course has an even lower failure rate/gate.

3.5. SYNCHRONOUS OPERATION

Almost all asynchronous problems can be solved by synchronous operation too. First synchronous circuits are much easier to test and service because one has a continuous clock which can be used to trigger oscilloscapes etc. If, for instance, one has to control the sequence of some operations a chain of univibrators can be used as shown in Fig. 13. Each univibrator in turn triggers the next one and so each of these adds to the possible error in timing. Besides this approach can be very expensive and uses more components for complex applications.

Fig. 14 shows the synchronous solution of the same problem. In this case the accuracy of the circuit is only determined by the clock generator which can be crystal controlled. The parts count is less for complex problems and so of course the reliability also goes up. And as already mentioned testing and servicing is quite simpler too. There are a lot of examples where synchronous operation offers great advantages as far as the reliability of the circuits is concerned

3.6. NOISE IMMUNITY

If reliable operation at high noise levels is necessary, one would use the slowest possible logic family or one of the high noise immunity logic families such as the Siemens FZ100 series. However, even with those specially designed families, standard C-MOS compares quite well if the supply voltage is properly chosen. The dynamic cross coupling noise immunity is shown in Fig. 15 [14, 15] for both the "0" level (Fig. 15a) and the "1" level (Fig. 15b). Fig. 16 shows the test circuit. The noise immunity increases with the C-MOS supply voltage for both states. So in order to obtain a high noise immunity the supply voltage should be high again. Below 2 nF cross coupling capacity the high noise immunity logic is better as far as noise immunity is concerned.

3.7. REDUNDANCY VERSUS SCREENING

By using standard components in parallel or serial redundancy single defective parts have no effect on circuit operation. However, one has to know the most probable failure mode, namely short circuit or open or use quadruple redundancy. If the most probable case of failure is a short, then, for example, two diodes in series could be used (one would still cut off). If the most probable failure is an open, then connecting two diodes in parallel would be the solution.

Since in most of the cases one does however not know the type of failure one would have to use quadruple redundancy, namely two diodes in series and two in parallel. This is quite expensive too and also very bulky (4 times the parts count), so except for a few rare cases where extreme reliability is needed and where in addition the parts are screened the redundancy method is hardly used.

3.8. COST VERSUS RELIABILITY

If a higher reliability of systems is needed, the necessary screened components are more expensive than those for commercial applications. An idea of the additional prices is given in the RAC report mentioned above [3]. If, however, one takes into account in the case of planes the cost of the overall system including service, then the seemingly more expensive Hi-REL unit may prove to be less costly after all.

There is a certain amount of fixed costs per IC package which adds to the actual price of IC's anyway. According to this TI publication [16] the fixed costs for

- Incoming inspection
- Storing
- Handling
- Insertion on p.c. board
- Wiring
- Soldering
- Testing
- Packaging
- Service

amount to about $1.-- to $2.--. This fixed price is already quite high compared to present day prices for SSI circuits. So because these costs are not to be avoided anyway, some additional screening may not make the overall system much more expensive at all. It has been shown that an order of magnitude less factory line repairs may be achieved by using screened parts in place of normal military types [17] . Since the reliability of the circuits is increased by going to MSI and LSI, both costs may be decreased and reliability increased at the same time by a lower number of parts.

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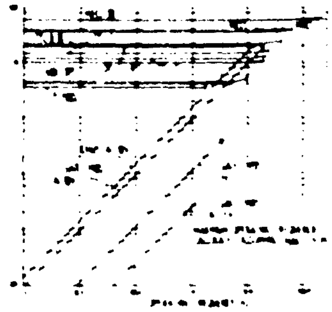

Fig. 1: Power dissipation as a function of operating frequency for several technologies

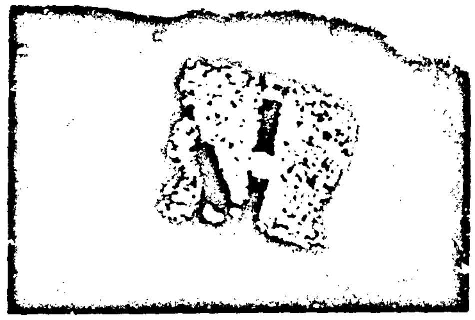

Fig. 2: Double bond on post

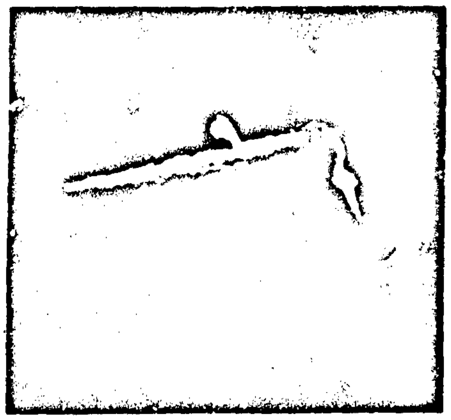

Fig. 3: SEM picture of metalization discontinuity at contact window

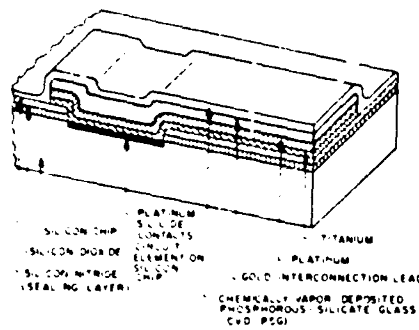

Fig. 4: RCA Trimetal system

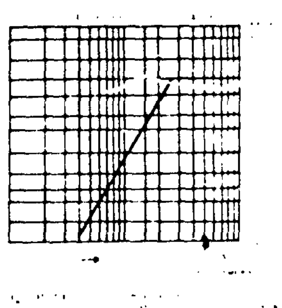

Fig. 5 Weibull probability chart for plastic C-MOS circuits

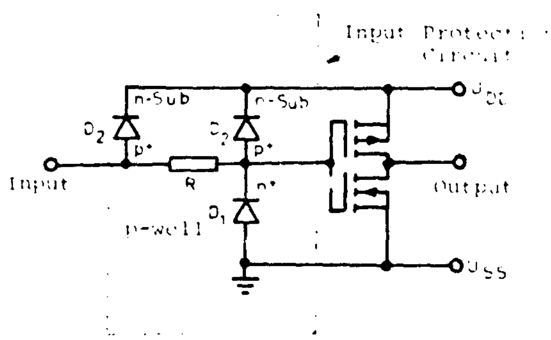

Fig. 6: C-MOS input protection circuit

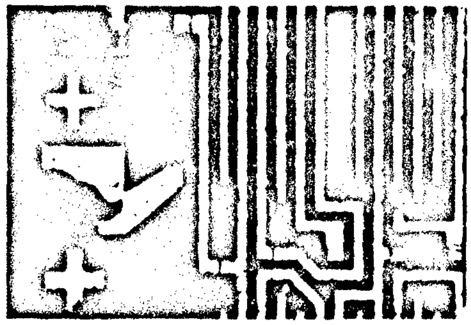

Fig. 7: Implementation of C-MOS input protection circuit

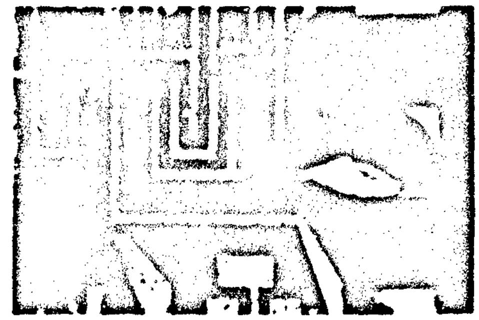

Fig. 8: Metalization burn-out

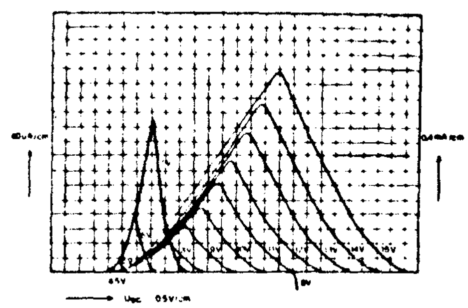

Fig. 9: Current drain depending on input voltage for CD4001 C-MOS circuit

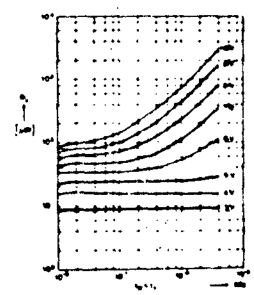

Fig. 10: Power dissipation versus rise and fall times of input pulses for CD4001 C-MOS circuit

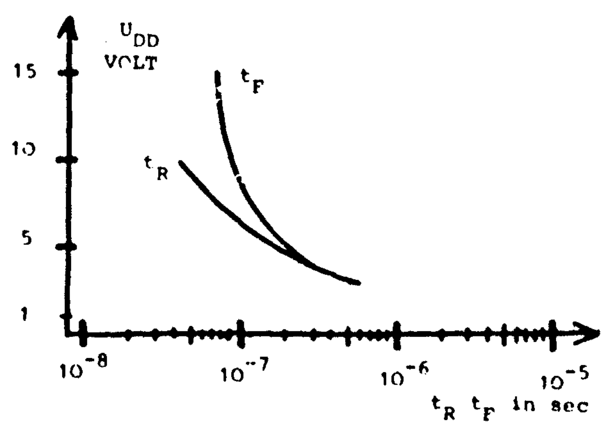

Fig. 11: Rise and fall times of CD4001 as a function of supply voltage, C_L = 50 pF

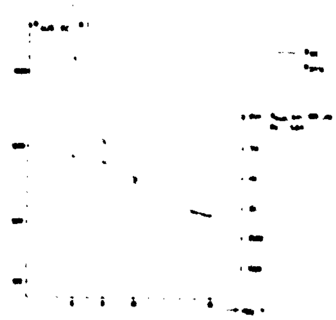

Fig. 12: Static and dynamic output impedance depending on supply voltage

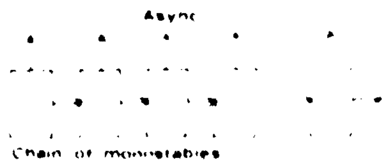

Fig. 13: Asynchronous solution of control logic

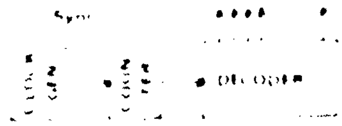

Fig. 14: [illegible]

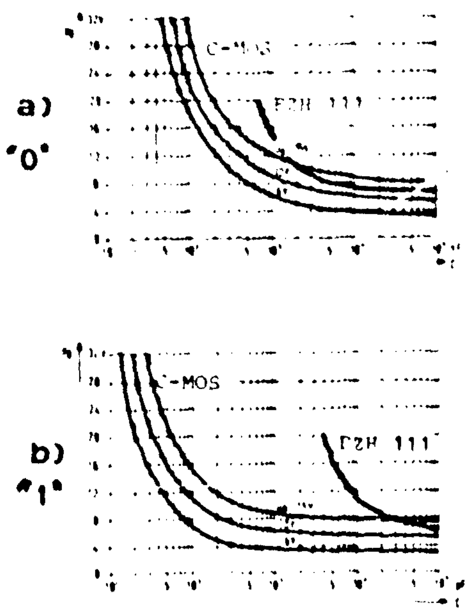

Fig. 15: Noise immunity of C-MOS CD4001 and Siemens FZ100 for "0" (a) and "1" (b) level

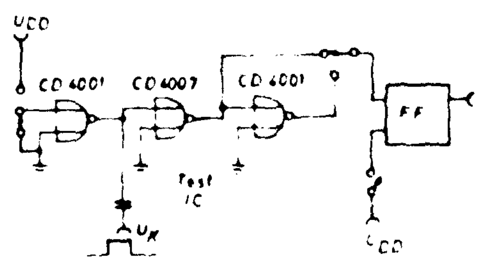

Fig. 16: Noise immunity test circuit

AVIONIC RELIABILITY AND
LIFE-CYCLE-COST
PARTNERSHIP

by

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SUMMARY

The use of life-cycle-cost/design-to-cost commitments on new weapon systems contracts has become necessary as a result of the high cost of acquisition and ownership of these systems. Life-cycle-cost analyses are being performed during proposal, development, and production phases of contracts to control potential weapon and avionic system cost problems. The cost analyses use life-cycle and logistic-support cost models as evaluation tools. One of the major contributors to the life-cycle cost of a weapon system is the operational reliability of the avionics. The interface of avionics reliability with life-cycle cost is discussed in this paper.

INTRODUCTION

The inclusion of life-cycle-cost/design-to-cost concepts in major defense system contracts is being emphasized to provide a cost discipline for use throughout the acquisition and operation of the system. Operational reliability of electronic equipment is one of the major parameters that influence life-cycle cost. Since the interface of reliability and cost under these concepts is rather new, it is the purpose of this paper to describe:

- What life-cycle cost is.
- Why the services are promoting life-cycle cost.
- What analysis techniques are used to evaluate life-cycle cost.
- What life-cycle-cost/design-to-cost requirements are contained in present contracts.
- The reliability interface with life-cycle cost during proposal, definition, and production phases.

LIFE-CYCLE COST DEFINED

Life-cycle cost of a system, as defined in Department of Defense Directive 5000.28, is the total cost to the Government of acquisition and ownership of that system over its full life. Life-cycle cost covers the cost of development, production, operation, support, and, where applicable, disposal (see Figure 1).

Development costs are all the research and development costs associated with the weapon system prior to production - the design, the hardware development, and the verification of the design.

Production costs are the costs associated with procuring the basic unit with propulsion equipment, electronics, armament, Government furnished equipment, and other weapon system items such as peculiar ground support equipment, peculiar training equipment, technical data, and initial spares.

Operations and support costs are those resources required to operate and support the system during its useful life in the operational inventory.

THE NEED FOR LIFE-CYCLE COST IN PROCUREMENT

The cost of procurement and operation of a weapon system has increased dramatically at the same time that defense budgets are being constrained. On the basis of historical trends (Figure 2), present projections into the future forecast an even worsening DoD budget squeeze. If the cost of all successor weapon systems continues to rise, there

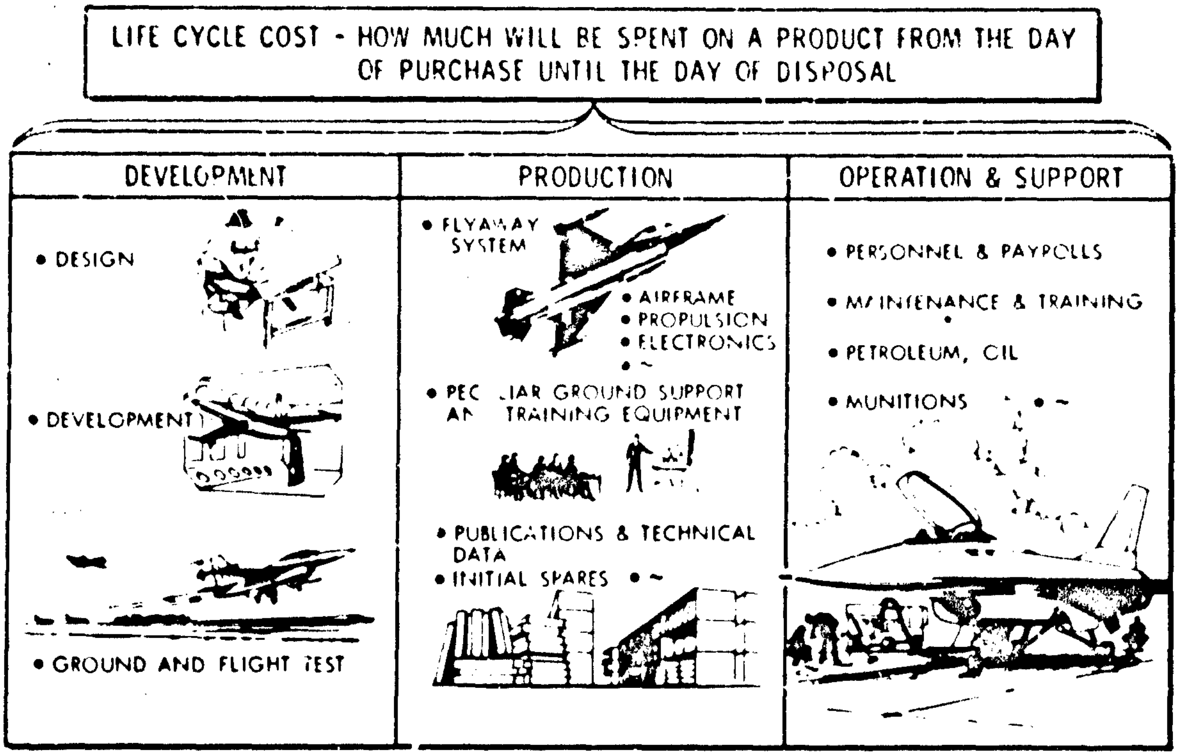


Figure 1 WHAT IS INCLUDED IN LIFE CYCLE COST?

simply will not be enough money to fulfill the requirements of these future programs. The services must obtain tools whereby they can estimate how much a weapon system is going to cost so that unaffordable systems can be rejected. In the present cost-squeeze environment, the services can procure weapon systems only if they know the cost - not only of the initial purchase, but also of the cost of owning the system.

Department of Defense Directive 5000.28, dated May 1975, establishes policy and guidance in the application of design-to-cost principles to the acquisition of defense systems, subsystems, and components. The design-to-cost concept contained in the directive states that the following will be accomplished:

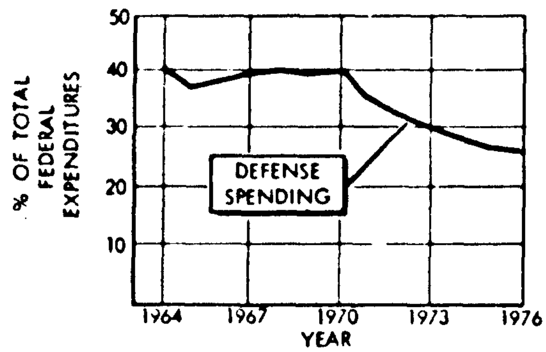


Figure 2 PERCENT OF FEDERAL EXPENDITURES ALLOTED TO DEFENSE

- o Life cycle cost objectives shall be established for each acquisition and separated into cost elements within the broad categories of development, production, operation, and support. As system definition continues, the cost elements are firmed into cost goals to which the system will be designed and its cost controlled.

- o During design and development, cost requirements and the achievement of cost goals will be evaluated with the same rigor as technical requirements and the achievement of performance goals. Practical tradeoffs between system capability, cost and schedules must be continually examined to insure that the system developed will have the lowest life-cycle cost consistent with schedule and performance requirements.

- o The cost goals established and "designed to" in the development phase will be extended into subsequent phases of the system's life cycle. Production cost will be rigorously controlled to the production goals.

o As the system is introduced, operation and support cost goals will be utilized to control initial outfitting cost, personnel, spares, rework, etc. In the operational feedback process, change requests generated by operational usage and feedback design engineering will reflect the use of design-to-cost principles and tradeoffs necessary to insure the lowest cost is obtained to achieve acceptable performance.

LIFE-CYCLE-COST ANALYSIS TECHNIQUES

Since the services are requiring that life-cycle cost be given equal consideration along with performance and schedule, both Government organizations and industry are obligated to create techniques and methodologies for use in quantitative evaluation and control of this cost during definition, design, development, production, and operational usage of a weapon system. A technique that is being developed presently is that of evaluation of life-cycle cost by use of analytical models.

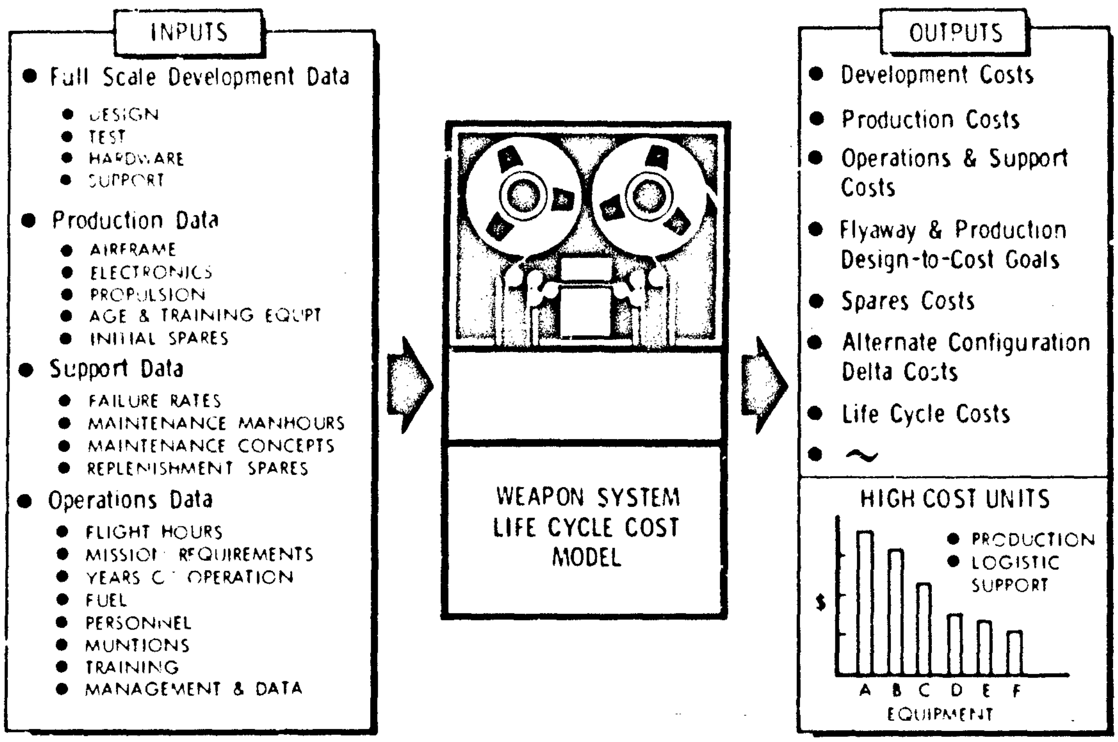


Figure 3 WEAPON SYSTEM LIFE CYCLE COST MODEL

The analytical model of a weapon system life-cycle cost can be described as a set of mathematical equations whose solution represents a close approximation of the true life-cycle cost for that system (Figure 3). Thus, the task of model development in this case is one of deriving a set of equations which are a function of those parameters that influence the life-cycle cost of the weapon system. (One of the major parameters that drives the life-cycle cost model is the operational reliability of equipment.) Such a model can serve as a tool to evaluate and control costs at the weapon system level by:

o Maintaining up-to-date estimates of weapon system cost during all phases of the program.

o Determining individual equipment and function cost goals.

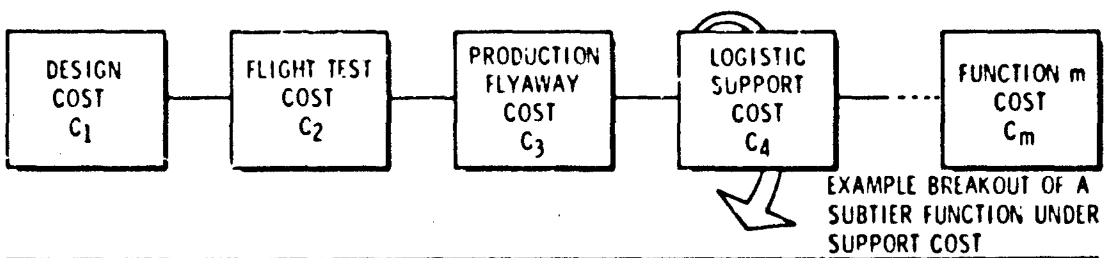
o Evaluating impacts of proposed design operational or reliability improvement change on life-cycle cost.

o Identifying equipment and function cost problem areas and determining impact on weapon system life-cycle cost.

o Providing life-cycle cost data for design, tradeoff and reliability improvement studies.

Life-cycle cost can be expressed mathematically in terms of all functions that generate cost (Figure 4). Because the cost of any one function adds to the total cost, the life-cycle cost equation (in its most general form) consists of the sum of all cost generators. Even though the weapon system equation is simply the sum of all costs, the cost expressions of the lower tier functions can take various forms as shown in Figure 4.

WEAPON SYSTEMS LIFE CYCLE COST → $LCC = \sum_{i=1}^{m} C_i$ ← COST OF ALL FUNCTIONS FROM DAY OF PURCHASE TO DAY OF DISPOSAL



$C_{4.4}$ = Intermediate and Depot Maintenance Costs

$$C_{4.4} = \sum_{i=1}^{m} \frac{(TFFH)(UF)(QPA)(1-RIP)}{MTBF} \begin{bmatrix} (RTS)(BMH)(BLR + BMR) + \\ (NRTS)(DMH)(DLR + DMR) \end{bmatrix}$$

WHERE:

- RTS = Fraction of Removals Repaired at Base Level
- NRTS = Fraction of Removals Returned to Depot
- MTBF = Mean-Time Between-Failures
- BMH = Average Manhours to Perform Base Shop Maintenance
- TFFH = Total Force Flying Hours
- [illegible]

Figure 4 WEAPON SYSTEM LIFE CYCLE COST MODEL EQUATIONS

Other models for items below the weapons system level can be used to obtain certain aspects of life-cycle cost. One of these is the ORLA (Optimum Repair Level Analysis), whose primary objective is to determine the recommended repair level of an item (any shop replaceable unit or repairable part). This objective is reached primarily as a result of economic decisions made in the analysis portion of the model. Item data (item spare cost, repair manhours, parts, cost and failure frequency, support equipment costs, training requirements, data requirements, non-economic factors, and operational data) are input to the model. Repair level costs for discarded-at-failure, base repair, and depot repair are calculated and compared so that a recommended repair level and alternatives can be obtained. A parametric sensitivity analysis is also performed for use as a design tradeoff aid. The optimum repair level output allows the determination of logistic support costs and sparing requirements, which are significant portions of the item life-cycle cost.

LIFE-CYCLE COST IN PRESENT CONTRACTS

Because specific contract provisions for life-cycle cost should be tailored to the weapon systems or equipment being procured, a standard set of specific contract terms and conditions do not exist. However, one can review the design-to-cost/life-cycle-cost (DTC/LCC) sections of the F-16 contract as an example of what is being included in present-day aircraft contracts. The F-16 contract includes life-cycle-cost related commitments associated with

o Design-to-Cost

o Air Vehicle and Support Cost Reduction Trade Studies

- o Logistic Support Cost
- o Reliability Improvement Warranties

F-16 DESIGN-TO-COST COMMITMENT

The current contract for full-scale development of the F-16 contains a section specifically for design-to-cost. The salient items of the section are summarized below:

- o Definition: Unit production flyaway costs are defined as the recurring and non-recurring costs (excluding all development costs) necessary to produce a complete aircraft. These costs include costs of airframe, propulsion, electronics, armament, other CFAE/GFE, engineering change orders of a recurring nature, and non-recurring production costs.
- o A prime objective of the development phase is to design to a cumulative average unit production flyaway cost of $3,842,525 expressed in FY 1975 dollars for 1000 production aircraft, at a maximum production rate of 15 aircraft per month.
- o The contractor shall control and track his portion of the design-to-unit-production flyaway cost of $2,323,074 throughout the development cycle. This figure excludes engine, radar, and Government furnished equipment.
- o The contractor is also expected to include as a management objective during development the control of future downstream operating and support costs. The Government will entertain requests for adjusting the design-to-cost goal at any time during the contract for real or demonstratable costs of ownership savings which would result in an overall life-cycle-cost benefit to the Government.
- o Two design-to-cost demonstration milestones are included in the contract with achievement dates of 19 months and 25 months after contract award. The objective of each milestone is to demonstrate the extent to which the contractor's portion of the flyaway cost will meet the goal of $2,323,074.

AIR VEHICLE AND SUPPORT COST REDUCTION TRADE STUDIES

Two separate sets of life-cycle-cost/design-to-cost design trade studies are to be performed by the contractor - one on the air vehicle and the other on supportability. The detailed definition of these trade studies is included in the contract. Award fees can be payable to the contractor by the Government in connection with these trade studies. The award fee will be based on an evaluation of the completion of these trade studies and the use of the results in the design of the air vehicle and support equipment.

LOGISTIC SUPPORT COST COMMITMENT

The contract contains two types of logistic support cost commitments - one on selected electronic equipment and one on the total aircraft minus the selected electronic equipment and minus the engine. The two commitments are called Target Logistic Support Cost-Correction of Deficiencies (TLSC-COD), and Target Logistic Support Cost-System (TLSC-SYSTEM), respectively. These commitments are summarized in the following paragraphs.

TLSC-COD Commitment

The contractor guarantees that the total Measured Logistic Support Cost (MLSC-COD) will not exceed a specified total Target Logistic Support Cost (TLSC-COD) for selected electronic First Line Units (FLUs) when the measured values are obtained (by a test program described below). The FLUs that are included in the TLSC-COD are shown in Figure 5.

The TLSC-COD value (one value for the total number of FLUs) was computed by the Air Force during the proposal phase on the basis of the contractor's estimates of FLU parameters such as mean-flight-time-between failure, base repair manhours, depot repair manhours, manhours expended for preparation and access, etc. The TLSC value was computed by inputing these parameters into the following abbreviated Air Force equation:

$$\text{TLSC-COD} = \sum_{i=1}^{n} C_{1i} + C_{2i} + C_{3i} + C_{5i}$$

where C_1 = initial and replacement spare costs

C_2 = on-equipment maintenance costs

C_3 = off-equipment maintenance costs

C_5 = support equipment costs

n = FLU types selected for inclusion in TLSC-COD.

The detailed formula for each "C" portion of the equation is included in the contract. The contractor's estimates for all parameters used are also contained in the contract.

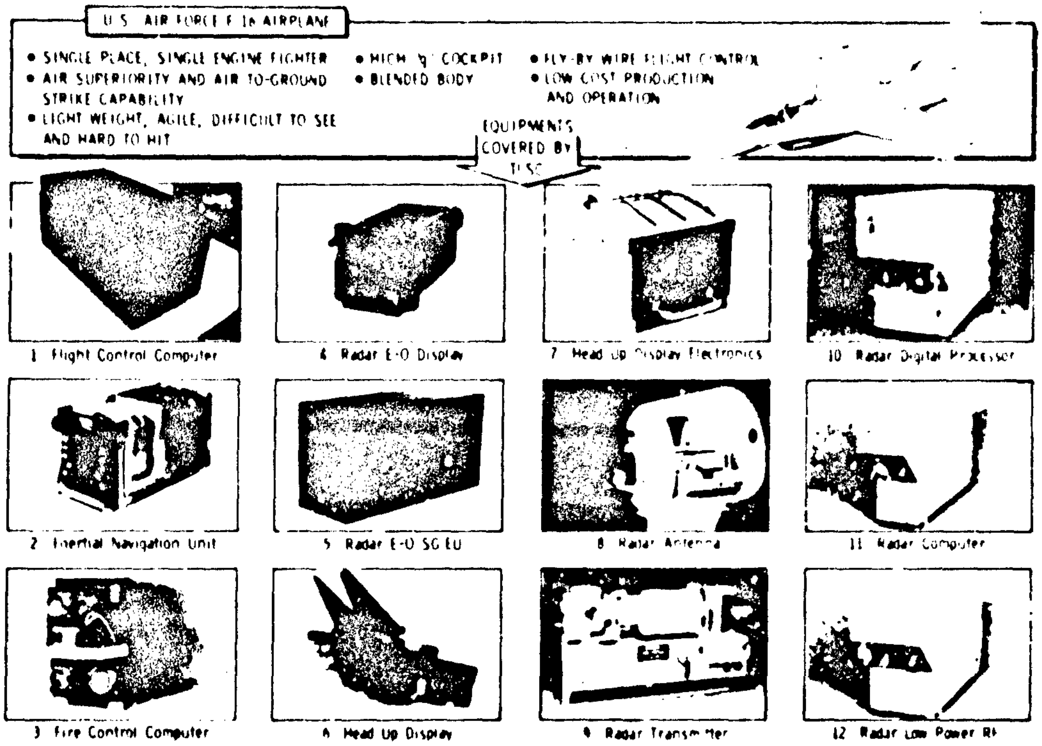


Figure 5 FLUs INCLUDED IN TLSC-COD

For purposes of determining the extent to which the TLSC-COD commitments have been realized, the Air Force will conduct a verification test to demonstrate operational suitability. The operational test will be conducted at a single base location no earlier than six months after full activation of the first operational squadron. The Air Force will be responsible for organizational-, intermediate-, and depot-level maintenance and will supply support for the selected FLUs. Support assets will be acquired by the Air Force in sufficient quantity on the basis of the original estimated equipment characteristics and the anticipated level of program activity during the test period. Maintenance procedures will conform with those prescribed in Air Force approved technical manuals. The test program will continue until 3500 total flying hours have been accumulated in airplanes from the squadron. All equipment maintenance actions will be recorded during that time.

The data collected on individual FLUs will be used in the same logistic support model formula to establish the measured logistics support cost (MLSC-COD). In the event that the total MLSC-COD exceeds the specified TLSC-COD by more than 25%, the contractor is required to indicate actions to correct the demonstrated support deficiency. If the MLSC-COD is less than or equal to TLSC-COD, the contractor is eligible for a separate award fee.

During the verification of MLSC-COD on selected electronic FLUs, one of the factors to be verified by measurement is the Mean-Flight-Time-Between-Failure (MFTBF) of each FLU. MFTBF is defined as follows:

$$MTBF = \frac{\text{total reported flying time during the test period}}{\text{number of failures on each FLU}}.$$

The definition of a failure will be consistent with that used for reporting and consolidating under the AFM 66-1 Maintenance Data Collection System. A failure will be considered as any departure from the required performance in excess of the allowable tolerance defined in specifications. A test failure will be defined as the following "how malfunctioned" codes and "action taken" codes (per definitions from Volume XI, AFM 300-4):

1. Any type 1 how malfunctioned code (item no longer can meet the minimum specified performance requirement due to its own internal failure pattern) in combination with an action taken code F (Repair), K (Calibrated-Adjustment Required), L (Adjust), or Z (Corrosion Repair).

2. Any type 1 how malfunctioned code in combination with an action taken code P (Remove and Replace), or S (Remove and Reinstall), provided the item was not found serviceable (B action taken code) at the bench check station.

3. Any type 1 how malfunctioned code where the removal of the FLU was required because of the failure of associated components attached or connected thereto. Action taken code G (Repairs and/or Replacement of Minor Parts, Hardware and Softgoods) will normally apply.

4. Any type 1 how malfunctioned code for which the FLU is subsequently found to be serviceable at bench-check or depot verification and the erroneous failure identification is due to inadequately described test procedures or test equipment developed, procured, or prescribed by the contractor.

5. Any type 2 how malfunctioned code of 553 (does not meet specifications, drawings, or other conformance requirements) or 602 (failed or damaged due to malfunction of associated equipment or item). A type 2 failure is when an item no longer can meet the minimum specified performance requirement due to some induced condition and not due to its own internal failure pattern.

6. A type 6 how malfunctioned code of 800 (No Defect-Component Removed and/or Reinstalled to Facilitate Other Maintenance), where such procedure is prescribed by a contractor-recommended test procedure or documented technical order.

TLSC-SYSTEM Award Fee

The contract contains a value for Target Logistic Support Cost-System (TLSC-SYSTEM). This value is the logistic support cost target for the total airplane minus the selected electronic FLUs and minus the engine. The value was computed during the proposal by the same methods used to compute TLSC-COD.

During the 3500-hour test on the first F-16 squadron, data will be gathered for verification of the TLSC-SYSTEM. In the event the total MLSC-SYSTEM is less than the TLSC-SYSTEM the contractor is eligible for an award fee.

RELIABILITY IMPROVEMENT WARRANTY (RIW)

The contractor agrees to provide (at firm fixed prices) either of the two options described below:

- A 48-month (or 300,000-flight hour) reliability improvement warranty on any or all of the First Line Units (FLUs) listed in Figure 5. (These are the same FLUs covered under TLSC-COD.)

- A 48-month (or 300,000-flight hour) reliability improvement warranty with MTBF guarantee on any or all of the FLUs listed in Figure 5.

Any of these options can be exercised on or before production go-ahead and before spares provisioning. In the event that the Air Force elects to exercise the RIW options on any FLU, the total TLSC-COD for all FLUs will be reduced by an amount equal to the associated logistic support of each FLU placed under RIW. Full discussion of the RIW is contained in an earlier paper in this volume.

LOGISTIC SUPPORT COST-RIW COMMITMENT SUMMARY

The logistic support cost commitment contained in the contract is in terms of logistic support cost targets for the system and for the critical electronic FLU's (Figure 6). If these targets are met the contractor qualifies for award fee. If the target for the critical electronics is not met the contractor can incur a correction of deficiencies. The RIW clause provides as an option cancellation of the logistic support cost commitment of any or all of the FLU's and replaces coverage of these selected FLU's by either a repair warranty (RIW) or a repair warranty with MTBF guarantee.

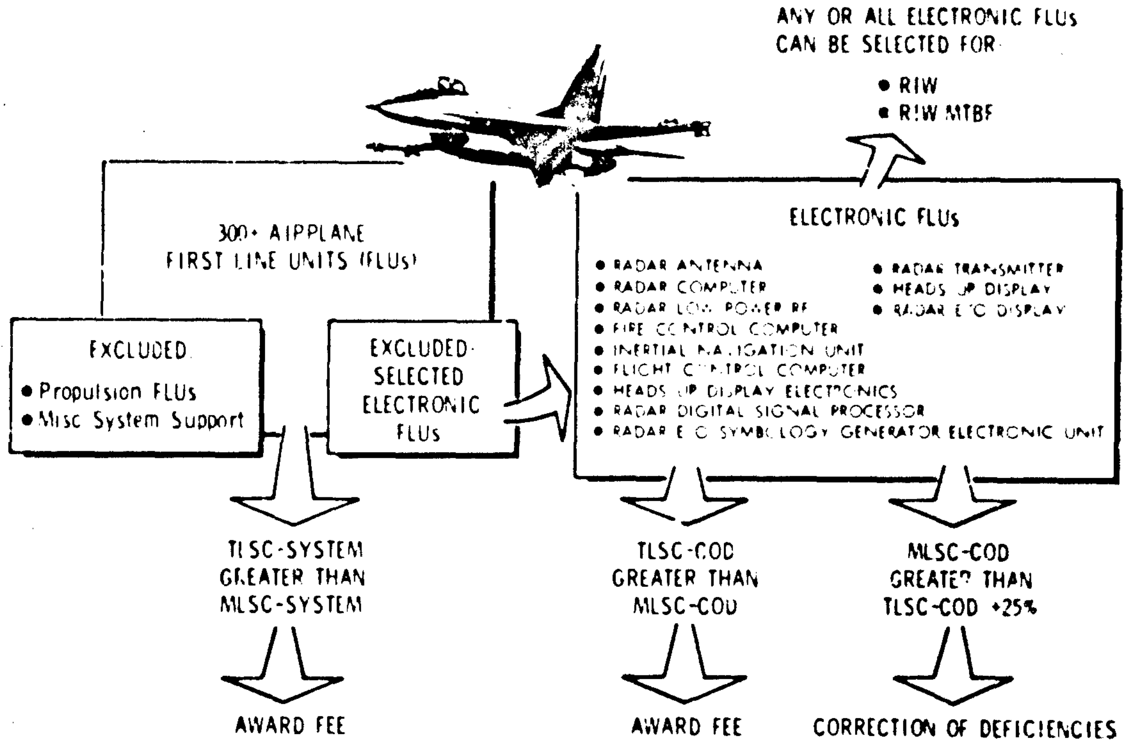


Figure 6 LOGISTIC SUPPORT COST - RIW COMMITMENT SUMMARY

INTERFACE OF RELIABILITY WITH LIFE-CYCLE COST

Hardware failure frequency is one of the major elements that drives up the life-cycle cost of a weapon system. The failure rate of the hardware impacts corrective maintenance costs, base and depot support and test costs, initial provisioning costs, reprocurement costs, transportation and packaging costs, and maintenance training costs. Any type of life-cycle-cost evaluation, tracking, and control must of necessity involve evaluation tracking and control of reliability. Any type of life-cycle-cost analysis must include reliability as one of its major inputs. As the services promote the use of new concepts in the area of life-cycle-cost procurement, new concepts in the area of reliability control will follow. A good example is the inclusion of reliability improvement warranties as a major life-cycle-cost reduction commitment.

RELIABILITY INPUTS INTO LIFE-CYCLE COST DURING PROPOSALS

During the proposal phase, reliability analyses are performed to determine the reliability characteristics of the various design configurations being evaluated prior to submittal of the recommended configuration with the proposal. Mission and hardware reliability predictions are accomplished at the system, subsystem, and lower levels. These predictions serve as inputs into reliability requirements analyses, design and technical trade studies, and life-cycle and logistic cost determinations.

The life-cycle-cost related effort by contractors during the proposal phase is a direct function of what is included in the contract. Over the last several years, major

emphasis has been placed on new concepts of procurement through design-to-cost/life-cycle cost. Contractors are responding. A good example of this response is the F-16 contract, which is the result of seven years of cost-reducing activity, as shown in Figure 7. This activity culminated in the Request for Proposal (RFP) for what is now the F-16.

When the RFP for full-scale development was received it required that cost data be provided to establish the unit production flyaway cost. The production reliability program costs were included in the establishment of this cost. Production reliability testing and the associated burn-in testing of the avionic equipments were priced at several million dollars. The results of the flyaway cost analysis are presented in Figure 8.

The RFP also required that the logistic support cost data on about 300 first line units (FLU's) be provided. These FLUs include all hardware, from avionic FLUs to hydraulic pumps to temperature control units. These data were required so that they could serve as inputs into an Air Force logistic support model. The model output results established the top contributors to total aircraft logistic cost. A working sheet presenting some of the top 20 contributors is shown in Figure 9. The top of the list was made up predominately of avionics (since the engine was not included). The logistic support cost for the top contributors was established and put into the contract as the Target Logistic Cost - Correction of Deficiencies (TLSC-COD) for the avionic equipment listed in Figure 6. The purpose of the TLSC-COD was to place major contractual emphasis on that equipment which was projected to contribute over 50% of FLU-related logistic support cost.

The main reason that the avionic FLUs were top contributors to the logistic support cost was the high frequency of failure of these units. One of the major tasks of reliability engineers during the proposal phase was to make estimates of the operational reliability of the avionics to serve as inputs into the logistic support cost model. Since TLSC-COD was to be verified during Air Force usage and the measurements were to be based on information from the Air Force AFM 66-1 Data system, it was decided to use 66-1 historical data as the base from which to make projections on F-16 avionics reliability. Predictions based on 66-1 data were thought to be the most representative of that which will be experienced in the field. Historical data were obtained on current airplanes such as the F-111, A7D, and the F4E. Extensive studies were performed by reliability and design engineers to determine the operational reliability of existing types of avionics from which the F-16 proposed avionics were derived. These operational reliabilities were established in accordance with the definition of failure given in the contract. The operational reliabilities of the similar or same-family avionic equipment (baseline) were then modified by certain factors to predict the reliability of F-16 avionic equipments. These factors are

- o A complexity ratio -- baseline equipment to F-16 equipment
- o Expected technology growth
- o Correction of known problems of operational hardware.

The RFP also contained a requirement to commit to reliability improvement warranties (RIW) with mean-time-between-failure (MTBF) guarantees. A full discussion on RIW is contained in another paper in this volume.

In summary, the contractual cost commitments are centered about design to cost, logistic support cost, and RIW. A quantitative overview of the relationship of these costs is presented in Figure 10.

RELIABILITY INPUTS INTO LIFE-CYCLE COST DURING DEVELOPMENT

During the development phase, the important tasks to be accomplished in the area of life-cycle cost are those related to tracking and control. Weapon system contracts such as the F-16 have unit production goals, logistic support requirements, and potential award fees tied to completion of trade studies. The successful accomplishment of these commitments requires full management attention. Cost tracking procedures such as shown in Figure 11 are initiated.

During F-16 development, the unit production flyaway cost goal of $2,323,074 is allocated down to all individual hardware and function element managers. Each element manager is provided with the allocation he is responsible for and with the up-to-date status of predicted cost. Reliability program costs are inherent in these cost targets.

Trade studies performed during development are used to evaluate opportunities for cost reduction or increase in system effectiveness. A system engineer designated leader executes a budget and time-limited task for each study. Study programs are milestone-oriented to allow progressive examination by engineering and program management. Reliability engineers input reliability impacts into each hardware-oriented trade study.

Logistic support costs are tracked and evaluated by use of the Air Force Logistic Support Cost Model. Predicted values of logistic support cost as compared to the specified TLSC values are generated, and potential problems are highlighted. Model analyses aid in the evaluation of (1) the avionic FLU's having the greatest cost impact, (2) trade-study alternates, and (3) life-cycle cost.

Early in the development phase, the MFTBFs that were used as inputs to the cost analyses are updated as the hardware becomes better defined. During development flight testing, as the weapon system is being flown by both contractor and Air Force personnel, the contractor has his first opportunity to establish an MFTBF tracking system in an environment similar to Air Force operations. During this time reliability engineers compare actual performance of the hardware during flight test with that included in the logistic support cost model and RIW commitments to uncover problem areas and initiate corrective action as required.

Past experience indicates that engineering change proposals (ECPs) can significantly increase production or support costs. Formalizing the cost evaluation and placing the design-to-cost/life-cycle-cost impact in each ECP assures proper recognition of cost impacts (Figure 12). Reliability is one of the main inputs associated with alternates that significantly change life-cycle cost or logistic support cost.

During the development phase the contractor selects subcontractors for major airplane equipment like the avionics. On the F-16, life-cycle-cost evaluations were part of the source selection process. Reliability and design engineers made a reliability prediction on each major avionic equipment proposed by a vendor. These predictions served as inputs into life-cycle-cost evaluations, which were then used in the source selection process. Extensive contact was made with subcontractors on life-cycle-cost contractual commitments (see Figure 13).

RELIABILITY INPUTS INTO LIFE-CYCLE COST DURING PRODUCTION

Reliability involvement in life-cycle-cost processes during the production phase of the F-16 centers mainly in the areas of accomplishment of RIW commitments and participation in the verification of the logistic support cost requirements. (The involvement of reliability in RIW during the production phase is discussed in another paper in this volume.)

The verification of TLSC-COD and TLSC-SYSTEM on the F-16 is to be accomplished by the Air Force with data accumulated during 3500 squadron flight hours. The contractor will supply representatives during the verification test to verify the authenticity of the observed data. Failure data obtained from the test will be analyzed by contractor design and reliability engineers. If the total MLSC-COD on the avionic FLUs exceeds the prescribed range in the contract, the contractor will investigate and formulate a corrective action plan which, when implemented, will bring logistic cost within the prescribed range. If the cause of failure to meet requirements is due to low reliability, the necessary hardware changes will be made to incorporate the necessary improvements.

CONCLUSIONS

Life-cycle-cost provisions in current weapon system procurement contracts are establishing cost as a parameter equal in importance with technical requirements and schedules throughout the design, development, production, and operation of the system. Since hardware failure frequency is one of the key parameters that influences life-cycle cost, any evaluation, tracking, and control of life-cycle cost must by necessity involve evaluation, tracking, and control of reliability.

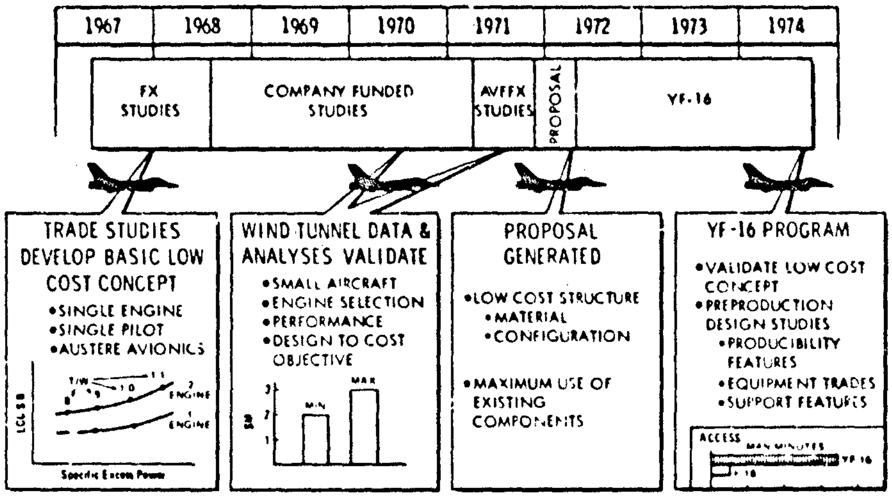


Figure 7 F-16 REFLECTS SEVEN YEARS OF MANAGEMENT DEDICATION TO COST REDUCTION

The fundamental low cost features of the F-16 have their basis in General Dynamics' work under Air Force funded FX studies initiated in 1967. In these studies, many variations were subjected to performance, flyaway cost, and life-cycle-cost analyses. From these studies it was determined that the F-16 design concept offered both performance and cost advantages over other approaches. Because of the potential of this design concept, General Dynamics continued work with company funds. The Air Force also saw the potential of this concept and funded additional studies in 1971. Subsequently General Dynamics' YF-16 proposal activities developed additional cost-reducing design features. After receipt of the YF-16 contract, General Dynamics instituted a two-year producibility program aimed at improved production management procedures and production cost design features. Both prior and subsequent to the flight test program, support/design studies were initiated. In summary, General Dynamics management emphasized cost as a factor coequal with performance and, by careful selection of design features, an inherently low-cost airplane design of small size, lightweight, simplicity, and low-risk technologies was produced.

UNIT PRODUCTION FLYAWAY COST

Goal	Basis
• Total Air Vehicle $3,842,525	• Cumulative Average
• General Dynamics .... $2,323,074 Controlled (Exl. Eng, Radar, GFAE)	• 1000 Airplanes
• "Design-To" Objective	• 15 Per Month
• Control and Track	• FY 75 Dollars

DEMONSTRATION MILESTONES

Demonstrate the Extent to Which the Airframe Manufacturer's Portion of the Cumulative Average Unit Production Fly-Away Production Costs for 1000 Production Aircraft at a Maximum Rate of 15 Per Month will Meet a Goal of $2,323,074 or Less Expressed in FY 75 Dollars

COST TARGET BREAKOUT

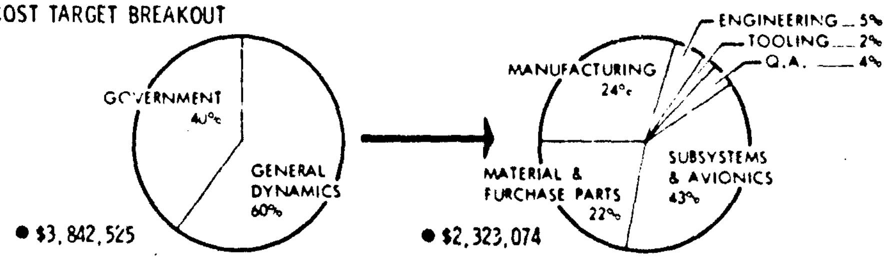
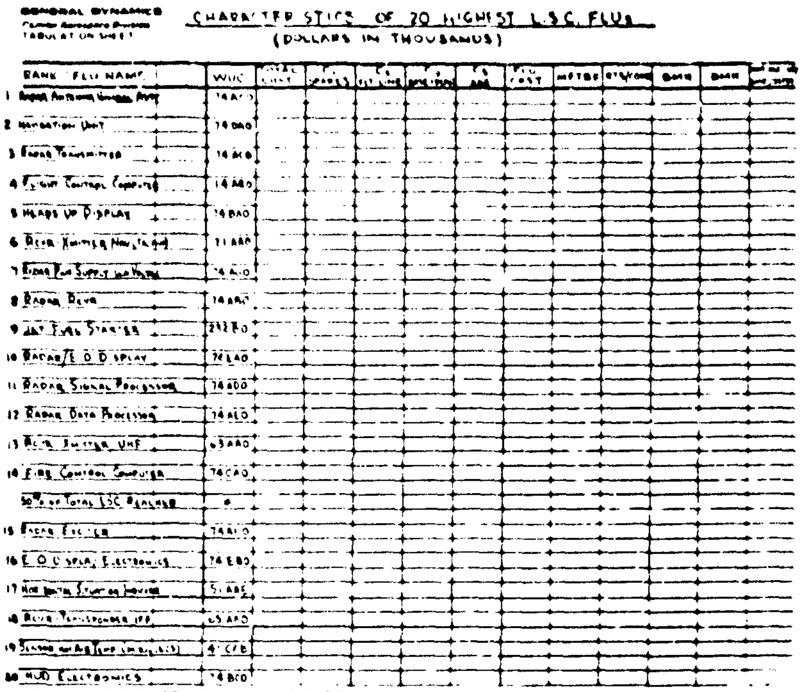


FIGURE 8 F-16 FLYAWAY COST CONTRACT TARGETS

The F-16 design-to-cost goal is a joint commitment, with both the Government and General Dynamics participating to control the average unit production cost of the aircraft. General Dynamics' portion of the cost target is a contractual commitment, and the ability to meet the commitment must be demonstrated during full-scale development. In order to meet its goal, General Dynamics has imposed a target on each of its cost-contributing departments, and they are obligated to spend no more in support of the production of the F-16.



GENERAL DYNAMICS
Tabulation Sheet

CHARACTERISTICS OF 20 HIGHEST L.S.C. FLUs
(DOLLARS IN THOUSANDS)

RANK FLU NAME	WUC	TOTAL COST	[illegible] SPARES	[illegible]	[illegible]	[illegible]	FLU COST	MFTBF	[illegible]	[illegible]	[illegible]	[illegible]
1 Radar Antenna [illegible] Assy	74A[illegible]0											
2 Navigation Unit	74DA0											
3 Radar Transmitter	74AC0											
4 Flight Control Computer	14AA0											
5 Heads Up Display	74BA0											
6 Rcvr Xmitter Nav [illegible]	71AA0											
7 Radar Pwr Supply Low Voltage	74A[illegible]0											
8 Radar Rcvr	74AA0											
9 Jet Fuel Starter	232E0											
10 Radar/E O Display	74LA0											
11 Radar Signal Processing	74AD0											
12 Radar Data Processing	74AL0											
13 Rcvr Xmitter UHF	63AA0											
14 Fire Control Computer	74CA0											
50% of Total LSC Reached	*											
15 Radar Exciter	74A[illegible]0											
16 E O Display Electronics	74EB0											
17 Horizontal Situation Indicator	51AA[illegible]											
18 Rcvr Transponder IFF	65AA0											
19 [illegible]	4[illegible]C[illegible]B											
20 HUD Electronics	74BC0											

- HIGH COST ITEMS AND DRIVERS
  - Identified in Proposal
  - Communicated to WBS Element Managers

FIGURE 9 TWENTY TOP LSC FLUs

Logistic support cost evaluation was part of the F-16 proposal process. High-logistic-support-cost FLUs were made visible. Responsible hardware and element managers for high-cost FLUs were briefed on reasons why FLUs were expensive (low reliability, high repair manhours, unit cost, etc.). Top management was briefed and improvement objectives were formulated.

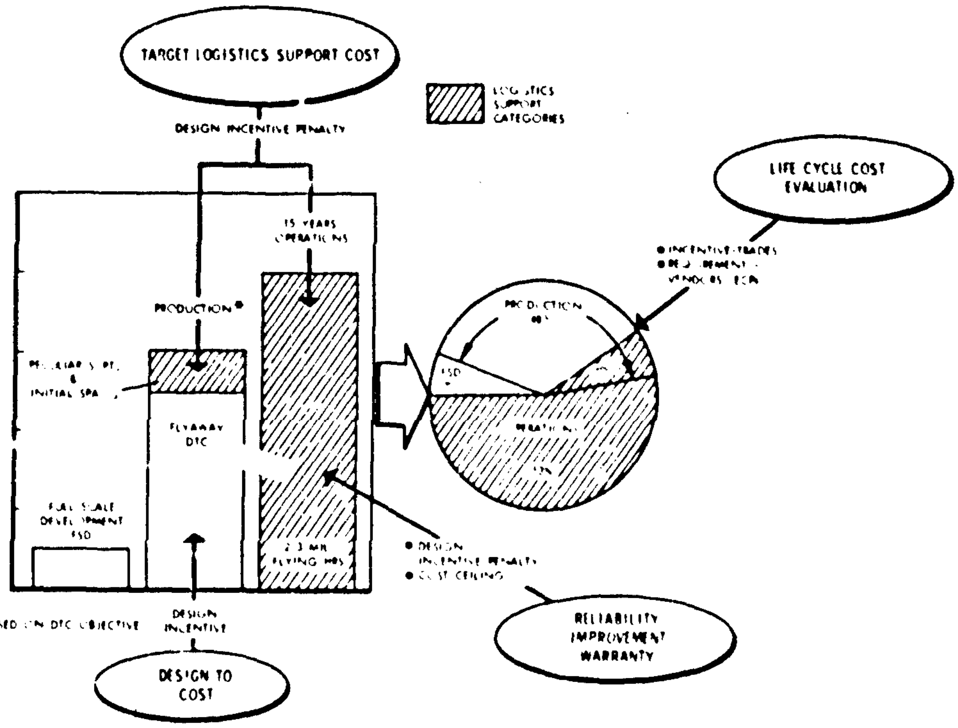


FIGURE 10 F-16 CONTRACTUAL PROVISIONS RELATED TO LIFE CYCLE COST

A variety of contract provisions were aimed at life-cycle control rather than a single control plan. Contract provisions apply to specific aspects of life cycle. TLSC applies to spares, support equipment, and repair cost. RIW applies to repair cost and reliability improvement. Design-to-cost applies to unit production flyaway cost.

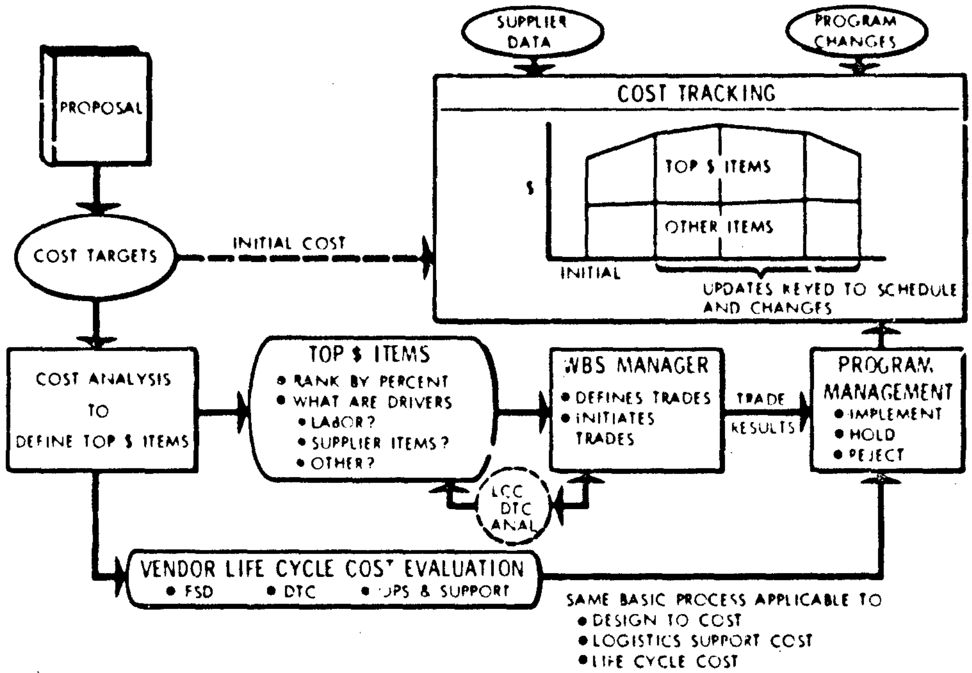


FIGURE 11 F-16 COST TRACKING AND CONTROL

Cost tracking and control for design-to-cost, logistic support cost, and life-cycle cost all follow the basic pattern shown above. Costs are assessed and targets established. High-cost items and associated drivers are identified. Hardware and function element managers identify cost-reducing trades and engineering changes. Management decides if recommendations on trades will be implemented. Costs are tracked to determine if cost is in control and if cost reduction measures are effective.

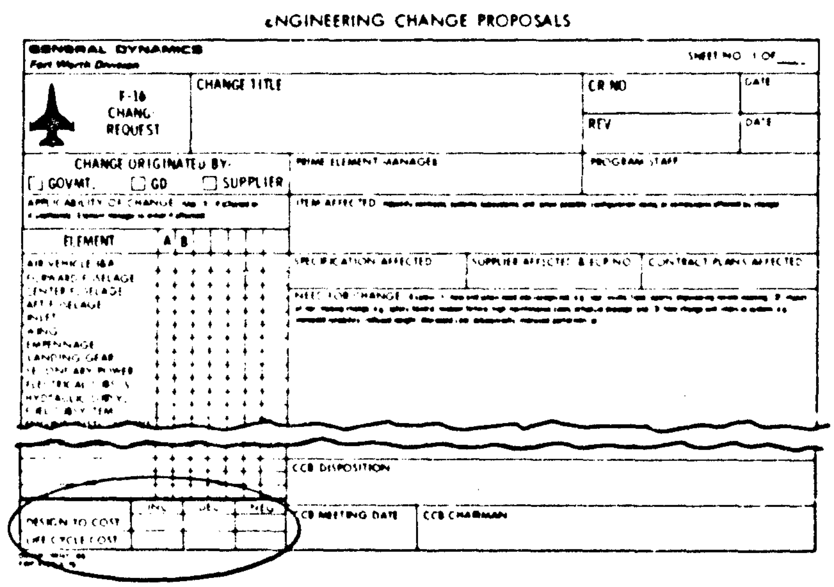


FIGURE 12 COST EVALUATION OF ENGINEERING CHANGES

All proposed engineering changes are processed on a F-16 Change Request as shown above. The change request is technically reviewed and an assessment of the design-to-cost and life-cycle cost is made. The Estimating Department makes a cost estimate of the change's impact on development and production. A preliminary estimate is made of logistic support cost based upon design information on the new characteristics of the FLU's lower level components and of the ground support equipment requirements.

CONFERENCES

GENERAL DYNAMICS
Fort Worth Division

9 April 1975
LWTjr:fb-086-0042

To: Jerry Wooley, W.M. Fowell, Dick Allen, C.A. Hardy, G.A. Hewitt, G.A. Cude, H.R. Darby

From: L.W. Taylor, Jr.

Subject: Meeting with Radar Representatives Reference TLSC/COD, RIW, RIW/MTBF, LCC and Design to Cost 3 April 1975

INPUTS TO SOURCE SELECTION

Analyses Completed	Analyses Pending
• Inertial Navigation	• Avionics AGE
• Heads Up Display	• Jet Fuel Starter
• Fire Control Computer	• Emergency Power
• Radar Display	• Radar
• Flight Control Computer	

FIGURE 13 SUBCONTRACTOR LIFE-CYCLE COST EVALUATION

Life-cycle cost was a key criterion in major subcontractor selections. Each potential subcontractor's equipment was evaluated for life-cycle cost. Reliability was one of the prime inputs into this evaluation. Prior to the final evaluation, considerable time was spent with subcontractors to assure proper input data for evaluations.

METHODES CONCRETES DE FIABILITE AVANCEE POUR LES EQUIPEMENTS ELECTRONIQUES DE BORD

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Service Technique des Télécommunications de l'Air, Paris-FRANCE

0 - INTRODUCTION -

Pour obtenir des matériels de haute fiabilité, il est nécessaire d'utiliser des méthodes adaptées et des moyens spécifiques. Au sein du Service Technique des Télécommunications de l'Air (STTA), les différentes étapes de l'élaboration de la fiabilité sont menées de la façon suivantes :

- composants : on cherche à obtenir des processus de fabrication conduisant à des dispositifs de fiabilité élevée.
- fiabilité prévisionnelle : les calculs correspondants sont effectués pour analyser les contraintes subies par les composants; améliorer la conception des circuits.
- essais de fiabilité et de déverminage : ils ont pour but de mettre en évidence les défauts de jeunesse et les pannes systématiques et de donner une estimation de la fiabilité proche de la valeur opérationnelle.
- clauses de fiabilité : il s'agit de s'assurer que l'objectif visé est atteint par des clauses de fiabilité garantie ou de maintenance forfaitaire.

Ces méthodes ont été appliquées récemment sur des matériels d'avionique développés sous responsabilité du STTA. Nous décrirons d'abord ces différentes méthodes et nous illustrerons par des applications à des cas concrets; ensuite, nous donnerons les résultats essentiels d'une étude qui avait pour but d'analyser sur un exemple particulier; l'efficacité de ces méthodes du point de vue "coût-fiabilité". Enfin, nous dégagerons les enseignements essentiels tirés de l'application de ces méthodes à des équipements connus.

I - POLITIQUE GENERALE -

Décrivons d'abord les différentes méthodes appliquées pour obtenir des équipements de haute fiabilité.

I-1. Niveaux composants.

Dans les marchés d'études et de développements des composants électroniques nouveaux, il est systématiquement introduit des clauses de fiabilité comprenant des essais en contraintes climatiques et mécaniques sévères. On trouvera un exemple de tels essais au tableau 1. Le but de ces essais est de faire apparaître les causes possibles de défaillance et de vérifier que les processus de fabrication conduisent à des dispositifs de fiabilité élevée.

Pour la fabrication d'un matériel, l'approvisionnement des composants est bien sûr de la responsabilité de l'industriel ; mais celui-ci doit choisir en priorité les "composants CCQ" ("Contrôle Centralisé de Qualité") c'est-à-dire ceux dont la qualité est contrôlée par un organisme agrée, le Service National de la Qualité (SNQ), ou ceux ayant fait l'objet d'un programme de sélection particulière chez le fabricant de composants. Mais ces derniers sont d'un prix de revient plus élevé.

I-2. Fiabilité prévisionnelle .

Le STTA demande en principe des calculs de fiabilité prévisionnelle dans le cadre des marchés d'étude de matériels ou systèmes nouveaux pour plusieurs raisons :

- ce calcul nécessite une décomposition complète du système et implique une analyse des contraintes de chaque composant après l'établissement des plans au bureau d'études, c'est donc une vérification supplémentaire.
- les premières estimations obtenues peuvent susciter des modifications pour améliorer les résultats (choix des composants, conception des circuits ....)
- les résultats peuvent servir aussi de base à un plan de maintenance.

En ce qui concerne le choix des données, on procède de la façon suivante :

Si une information satisfaisante concernant l'utilisation d'un module dans les mêmes conditions que celles du sujet à l'étude est disponible, elle doit être utilisée en premier.
En dehors de cette possibilité, les données des taux de défaillances provenant de sources générales peuvent être utilisées, mais doivent être précisées et justifiées. L'utilisation du HDBK 217 ou d'un document équivalent établi par le Centre National d'Etudes de Télécommunications (CNET) est recommandée. Quand cela est possible, on s'efforce de reprendre les calculs selon des sources différentes, afin de mettre en évidence la sensibilité des résultats.

I-3. Essais de Fiabilité .

Les essais concernent les matériels prototypes ou de série. Ils ont pour but d'améliorer la fiabilité par la mise en évidence des défauts systématiques à une période où il est encore possible techniquement et financièrement d'y porter remède, et de donner une estimation de la fiabilité plus proche de sa valeur opérationnelle.

On cherche à réaliser en laboratoire des conditions d'environnement climatiques et mécaniques proches des conditions réelles d'utilisation.

Les essais effectués sont comparables à ceux décrits dans la norme MIL 781 A ou dans la spécification française équivalente (CCT 190).

On indiquera plus loin un exemple d'application de ces essais à un répondeur de bord (IFF)

I-4. Déverminage .

Le déverminage est l'opération qui consiste à faire fonctionner le matériel, sous contraintes ou non, avant la recette pour éliminer les défauts de jeunesse. Il est très souvent effectué par l'industriel soit pour avoir plus de chances de satisfaire aux conditions de recette, soit pour éviter d'avoir à procéder à trop de réparations sous garantie, soit sur demande du service tecnique.

La durée de ce déverminage est variable d'un industriel à l'autre et dépend de la complexité du matériel.

Il semble qu'un essai d'une vingtaine d'heures sous contraintes thermiques et mécaniques prolongé jusqu'à 100 heures par un rodage (fonctionnement simple) soit assez efficace pour éliminer les défauts de jeunesse.

Mais certains industriels le prolonge jusqu'à 200 ou 350 heures. On trouvera plus loin des exemples particuliers de déverminage.

1.5. Fiabilité garantie .

Afin d'obtenir des équipements de haute fiabilité un programme d it introduire une Clause de Fiabilité Garantie dans le contrat   achats. Ce problème particulièrement important sera abordé dans une autre conférence.

2 - APPLICATIONS DES METHODES -

Pour illustrer ces méthodes générales, nous allons décrire une application dans le cas d'un radioaltimètre, le matériel est un bon exemple d'une part parce qu'il présente une excellente fiabilité (MTBF supérieur à 2000 h en exploitation); d'autre part, il se prête à une analyse de rentabilité non seulement parce que le coût des opérations de promotion de la fiabilité n'est pas négligeable dans le prix de revient, mais aussi parce qu'un véritable "suivi" de la fiabilité à tous les stades du développement et de la production a été installé, ce qui donne une source très importante de renseignements et a permis une critique sur l'efficacité de ces procédés, comme nous le verrons plus loin. Nous illustrerons également ces méthodes par leur application sur d'autres matériels, en particulier des répondeurs de bord IFF.

2.1. Le matériel .

Le matériel de référence est le coffret émetteur-récepteur d'un radio-altimètre.

Pour en donner une brève description, nous dirons qu'il comporte essentiellement un générateur "solid-state"hyperfréquence modulé en fréquence (module Z1), un récepteur homodyne Z2 suivi d'un amplificateur Z3 commandant un discriminateur Z7 ; le signal du discriminateur, après identification du signal reçu par un module Z6 de logique de recherche-poursuite, commande le modulateur Z5 (donc fonctionnement en boucle fermée); les modules Z4 et Z8 transforment les signaux internes en signaux d'altitude exploitables et l'alimentation Z9 délivre à l'ensemble les tensions utiles. Sa complexité peut être définie par les chiffres suivants: 600 composants, dont 70 transistors, 30 circuits intégrés linéaires et 5 circuits intégrés logiques.

2.2. Fiabilité prévisionnelle .

Deux méthodes ont été utilisées pour prédire la fiabilité.

Au stade développement, la méthode maximum-minimum décrite dans le HDBK 217 A a permis de prédire une gamme de valeurs de MTBF alors que l'étude n'était pas terminée.

Une fois connus les schémas retenus, une deuxième évaluation a été faite à partir des données du RADC 68. Dans ce but une analyse des contraintes réalisées sur chaque composant a permis de s'assurer que les limites dangereuses d'utilisation des composants n'etaient pas atteintes.

Ces seconds calculs ont révélé une augmentation d'environ 30 % du MTBF par rapport à la première évaluation, et une répartition différentes des pourcentages d'influence des divers types de composants, notamment l'importance prépondérante des semi-conducteurs et circuits intégrés (70 %), dans le taux de pannes.

Les calculs ont bien sûr montré la répartition par modules de la fiabilité, comme indiqué dans le tableau 2.

2.3. Choix des composants .

Le calcul de fiabilité prévisionnelle ayant fait ressortir l'importance des semi-conducteurs et l'expérience ayant montré que les diodes étaient généralement bonnes, un effort particulier a été fait sur les transistors et circuits intégrés. Ils ont été approvisionnés sur programmes de sélection particuliers effectués chez le fabricant dont les rapports font état d'un taux de déchet très variable d'un lot à l'autre ; la moyenne générale est de 23% de déchets aux essais de sélection avec des valeurs extrêmes variant de 1 à 70% .

En dehors des semi-conducteurs, on a considéré avec attention la fiabilité des condensateurs chimiques et des relais électro-magnétiques. Ces deux types de composants ont également été vieillis artificiellement, sous tension. Par exemple, pour les condensateurs chimiques, le critère de sélection était le courant de fuite après vieillissement ; pour les relais, on s'assurait d'un fonctionnement correct.

Pour les autres composants, dont l'influence sur la fiabilité est moindre, comme le montre l'analyse de fiabilité prévisionnelle, ils ont été approvisionnés sur listes reconnues par l'administration militaire et par les organismes d'état de contrôle de qualité (CCQ).

2.4. Déverminage .

2.4.1. Radioaltimètre .

Pour ce radioaltimètre, les opérations de déverminage ont été faites à 3 niveaux .

a) Après câblage-montage, deux modules subissent un vieillissement en cycles thermiques d'une centaine d'heures. L'un des modules, Z1, générateur hyperfréquence, doit subir une stabilisation sous tension avant règlage final ; cette stabilisation joue un rôle important de déverminage car elle élimine les transistors UHF défectueux et certaines capacités céramique.
Un autre module, Z9, l'alimentation, mérite un déverminage à p rt et avant enrobage dans le vernis, vu son taux de déchet élevé.

b) Après assemblage et réglage, les ensembles complets subissent, sous tension nominale, un déverminage en cycles thermiques (-40°C, +70°C) d'une centaine d'heures, et en vibrations.

c) Le matériel subit enfin un rodage de 200 h dans le laboratoire.

2.4.2. Une expérience plus récente de déverminage porte sur un répondeur IFF de bord.
Le but de l'étude était de procéder à des essais pour déterminer le temps de déverminage que doivent subir les équipements pour avoir une fiabilité opérationnelle optimum dès le début de leur utilisation.

On a utilisé la méthode suivante :
24 appareils ont été prélevés sur la production et ont subi des essais de 800 h dont 400 en fonctionnement.

Le cycle des essais a été bati à partir des essais de fiabilité décrits dans les normes MIL 781 A ou CCT 190 : soit un cycle de température de - 55° à 55°C et des vibrations de 0 à 100 Hz à 2 g appliquées 10 mn par heure.

Pour le test des équipements, on a utilisé le test interne du répondeur commandé toutes les 30 secondes, et on a procédé à des vérifications bi-quotidiennes pour déceler les éventuelles dégradations de performances des principales fonctions.

Une fiche individuelle était établie pour chaque équipement

Analysons les résultats obtenus :
L'ensemble des équipements a totalisé environ 10000 heures de fonctionnement et ces essais ont conduit à deux types d'action.

a) D'une part le tracé de la courbe taux de défaillance en fonction du temps, a permis (tableau 3) :
   - de mettre en évidence les 2 premières parties de la "courbe en baignoire", caractéristique des équipements électroniques,
   - de procéder à une estimation du MTBF avant déverminage selon les règles bien connues des lois d'intervalles de confiance. Les valeurs correspondaient d'ailleurs aux premiers résultats obtenus en exploitation.
   - de déterminer le temps de déverminage nécessaire pour atteindre le "fond de baignoire"; la courbe étant bien caractéristique il a été aisé de voir qu'au bout de 100 h on avait éliminé les principaux défauts de jeunesse.
   - d'estimer le MTBF après déverminage. Il s'avère que ce dernier permet d'augmenter de 70% le MTBF initial.

b) D'autre part le dépouillemnt des types de pannes a révélé quelques points faibles de l'équipement, notamment des mauvais fonctionnements d'éléments mécaniques au froid

et quelques types de composants défectueux.

Des remèdes ont été étudiés, certains allant jusqu'à la refonte totale de certains circuits. On peut espérer une augmentation très substantielle du MTBF après l'application des modifications sur les équipements à produire.

Les modifications et enseignements techniques tirés de ces essais ont été les suivants : renforcement des métallisations des trous de connexions de circuits double face et utilité des essais de sélection pour un type de circuits intégrés. Il est intéressant de noter que l'augmentation du prix des composants sélectionnés chez les fabricants de circuits intégrés n'a pas été répercutée sur le prix du matériel ; il semble qu'elle ait été compensée par une diminution du coût de fabrication-contrôle-réparation des cartes en cours de production où le nombre de défaillance était très élevé avant le déverminage des circuits.

Ces actions ont été très efficaces puisqu'aucune panne de métallisation n'est apparue lors des essais et que les circuits intégrés ont montré une meilleure fiabilité.

2.5. <u>Essais de fiabilité</u> .

On effectue assez souvent des essais de fiabilité selon les normes MIL 781 A ou CCT 190.

On va décrire une application particulière de ces essais de fiabilité à un autre type de répondeur de bord IFF.

Un des buts de cet essai de fiabilité était d'obtenir, outre l'amélioration de la fiabilité, la meilleure connaissance possible du MTBF en exploitation réelle. Il a fallu donc faire plusieurs adaptations des cycles d'essais décrits dans la norme MIL 781 A pour se rapprocher au mieux des conditions réelles mécaniques et thermiques (cf.tableau n° 4).

Les principaux résultats obtenus de ces essais sont les suivants :

- comparaison des MTBF obtenus par le calcul prévisionnel, par les essais de fiabilté, en exploitation réelle :
  - . par le calcul (RADC) : 600 h
  - . par les essais : 470 h
  - . en fonctionnement réel 660 h
- On a pu également obtenir d'autres renseignements :
  - . très grande influence de la loi de variation du cycle de température et de vibration.
  - . détermination de la durée optimale du déverminage (30 heures dans ce cas particulier)
  - . une connaissance sûre du comportement de l'équipement, permettant la négociation de Clause de fiabilité garantie.

De façon très générale, le STTA considère comme très fructueux les essais de fiabilité en laboratoire; au niveau des prototypes et de la préserie, ils permettent de détecter les "erreurs" de fiabilité; au niveau de la série, ils donnent une approximation satisfaisante du MTBF opérationnel, qui permet une meilleure maintenance (calcul des rechanges) et donne des éléments indispensables pour l'introduction dans un contrat d'une clause de fiabilité garantie.

3 - EFFICACITE DES METHODES -

3.1. Généralités.

Nous venons de voir que, pour obtenir une bonne fiabilité, il faut des méthodes à tous les niveaux : lors de la conception de l'équipement, dans le choix et la sélection de ses composants constitutifs à travers les procédés de fabrication retenus, aussi bien qu'à l'occasion d'essais de toutes sortes ou d'une politique de contrôle de qualité; aussi, chaque phase de la vie d'un équipement électronique permet des actions en faveur d'une meilleure fiabilité; à chacune de ces actions correspond un coût accessible à partir de la comptabilité analytique de l'unité industrielle qui produit l'équipememnt mais il est le plus souvent impossible d'associer également une efficacité à chacune des actions considérées. Cette situation tient à la nature probabiliste de la fiabilité - et des grandeurs qui lui sont associées (MTBF, taux de panne) - qui en rend malaisée la mesure et à l'insuffisance des méthodes analytiques de caractère général.

Une étude spécifique a été lancée et avait pour objet d'extraire, à partir de données réelles, des relations quantitatives liant l'amélioration de la fiabilité d'un équipement électronique à l'accroissement correspondant de son coût. Ces relations devaient déterminer, en quelque sorte, le "coût-efficacité" des différents moyens que l'on peut mettre en oeuvre dans la réalisation d'un équipement électronique pour en augmenter la fiabilité ; leur utilisation permet ainsi de choisir le juste poids à donner à chacun de ces moyens afin d'atteindre le plus économiquement possible un objectif de fiabilité fixé. Pour que cette étude soit concrète, elle a été appliquée au radioaltimètre dont nous avons déjà parlé.

3.2. Procédé d'analyse des méthodes.

L'étude utilisait les informations recueillies sur chaine de production du radio-altimètre qui a fourni en trois ans plus de un millier d'équipements ce qui a permis d'accumuler un très grand nombre de données :

- des données de défaillance survenues à l'équipement ou à l'un de ses sous-ensembles lors d'essais de rodage; nous admettrons en première approximation que le MTBF ainsi estimé est un indicateur suffisament fidèle de la fiabilité opérationnelle de l'équipement ce qui a été vérifié par ailleurs.
- des données d'identification de toutes les opérations effectuées sur la chaîne de fabrication depuis son démarrage (approvisionnements, essais, contrôle, etc...)

Les renseignements disponibles sur 3000 interventions ont été transcrits sur un fichier d'environ 20000 blocs de 80 caractères.

Pour juger de l'efficacité des méthodes d'augmentation de la fiabilité on a utilisé toutes les ressources de l'analyse statistique et factorielle.

L'analyse d'efficacité des opérations de fiabilisation a été d'autre part facilitée énormément par la qualité des réparations à chaque stade :

une première analyse montre qu'au niveau de l'équipement il n'y a pas d'influence marquée d'une intervention sur la vie ultérieure de l'équipement et donc que les traitements de fiabilisation ont des conséquences indépendantes au niveau d'un équipement donné.

3.3. Critique des méthodes.

Les différentes actions exposées précédemment conduisent à une analyse critique à tous niveaux :

-Critique du dossier de fabrication et du calcul de fiabilité prévisionnelle-

On peut d'abord contrôler les prévisions de fiabilité.

Les semi-conducteurs font effectivement l'essentiel de la fiabilité à long terme de l'équipement, mais les circuits intégrés jouent un rôle primordial, d'autant plus que dans ce cas la procédure de sélection en fiabilité est assez peu efficace.

La répartition des pannes suit relativement bien les prévisions : les modules 71, Z6 et 29 sont effectivement les plus fragiles mais si les défaillances de 71 et Z6 sont neutres pour la fiabilité à long terme, un taux de défaillance élevé les diodes de puissance dans l'alimentation est signe certain de fragilité et de fatigue vraisemblable à une échéance plus ou moins brève.

-Critique de la sélection des composants -

Pour les capacités chimiques, le vieillissement avec surveillance du courant de fuite a été efficace, d'autant plus que la longue période de repos qui a suivi ce vieillissement, avant montage et remise sous tension, a permis à nombre d'éléments douteux de continuer à évoluer et d'être éliminés : pour ce type de composant, l'action des cycles de vieillissement est maintenant bien connu et permet d'envisager un mode de sélection du même type, plus rapide.

Pour les circuits intégrés et les transistors à effet de champs, le mode de sélection s'est révélé peu efficace.

Les lots sur lesquels le fabricant donne un taux de déchet en essais de fiabilisation supérieur à la moyenne ont lors les opérations suivantes et en exploitation une mortalité supérieure également. Le renforcement des essais de fiabilisation et des contrôles a augmenté le taux de déchet lors de ces essais sans que l'influence s'en fasse sentir par la suite.

Il n'est toutefois pas certain que cette sélection n'ait eu aucun effet bénéfique : à cause des déchets importants en fiabi-

lisation et aussi de doléances répétées, le fabricant a livré, sur la fin de la période de fabrication, des lots très nettement meilleurs.

Pour les transistors bipolaires, l'analyse factorielle ne permet pas de tirer de conclusions : en exploitation comme en fabrication, le taux de défaillance reste bas et semble conserver un caratère parfaitement aléatoire.

- Critique des déverminages -

- Des opérations de déverminage ont été effectuées sur deux modules Z1 (générateur UHF) et Z9 (alimentation). Les analyses montrent le résultat suivant :

le comportement de ces deux modules est très différent : autant le déverminage semble efficace sur le module Z9, autant le résultat semble peu convaincant pour le module Z1 bien qu'un vieillissement sous tension soit absolument nécessaire avant réglage final, pour pallier la dérive (souvent destructive) des caractéristiques des transistors.

- Pour le déverminage des ensembles complets, on constate que près de la moitié des défaillances des 20 premières heures correspondent à des défauts de fabrication qui, dans ce cas, sont parfaitement éliminés et n'ont plus d'incidence sur la suite ; la conclusion qu'on peut en tirer est que ces 20 premières heures de déverminage ont permis de diminuer d'environ 40 le nombre de défauts prématurés en exploitation : ces 20 premières heures jouent bien le rôle de déverminage qu'on attendait de l'essai.

Les autres défauts détectés pendant ces heures initiales de déverminage sont du même type que ceux détectés par la suite de l'essai. L'action de déverminage n'est évidente que pour les inductances, les capacités chimiques et pour les diodes redresseuses de l'alimentation.

Pour les circuits intégrés et les transistors à effet de champs, le taux de défaillances pendant l'essai est un indice de la qualité du lot.

Reste à interpréter l'action globale de l'essai : a-t-on éliminé par cet essai la majeure partie de défaillances à plus ou moins court terme en exploitation ? Si on analyse les différents aspects, on peut conclure que l'efficacité du déverminage est certaine, mais qu'en corollaire on provoque des défaillances qui n'on aucun rapport avec la fiabilité lorsque le déverminage pratiqué est trop dur, surtout si on le prolonge au delà de 20 heures.

- Critique du processus industriel de régulation de la fiabilité -

Deux boucles de contre-réaction principales étaint sensées assurer une certaine stabilité de la qualité et de la fiabilité du produit fini : une contre-réaction basée sur la qualimétrie du contrôle industriel d'une part, et une seconde baxée sur la mesure de MTBF en essais de déverminage d'ensemble. L'analyse du processus a montré que la fonction de transfert des boucles de contre-réaction était inadaptée, notamment à cause de sa constante de temps

En effet un contrôle industriel dont les réactions interviennent trop longtemps après la fabrication est inefficace si pendant le temps écoulé entre la détection des premiers défauts,

la détermination de leur cause (outillage défectueux, personnel inadapté) et le remède, de nombreux équipements continuent à subir les même défaut.

Pour la boucle de fiabilité basée sur les résultats en déverminage, son effet régulateur à court ou moyen terme est nul puisque le taux de défaillance à ce niveau ne représente pas la fiabilité du matériel.

3.4. ELEMENTS DU COUT DES OPERATIONS DE FIABILISATION .

La prime à payer pour produire un radioaltimètre de bonne fiabilité avec le processus de fabrication initial était d'environ 30 % du prix de revient de l'équipement, le coût de la sélection des composants y intervenant pour 15% et les opérations de déverminage et de contrôle pour un pourcentage a peu près identique.

A titre d'exemple, on peut faire un tableau (cf.tableau 5) de la relation coût-efficacité des opérations de fiabilisation des semi-conducteurs actifs, dont le taux de défaillance est important par rapport au taux défaillance global de l'équipement : ces semi-conducteurs actifs sont en cause dans deux défaillances sur trois.

En moyenne, la formule d'approximation de la sur-prime S qui a été payée au fournisseur pour les opérations de sélection peut s'écrire :

$$S = 1\not{8} + P/3$$

L'analyse d'efficacité a suggéré un moyen de diminuer notablement le budget "fiabilité" et sans doute de le limiter à une sur-prime de l'ordre de 10%. En effet, l'analyse montre que malgré toutes les précautions, la fiabilité du matériel reste une fonction directe de la qualité des pièces détachées.

La procédure à retenir pour obtenir le meilleur compromis prix-fiabilité serait la suivante.

- même si l'efficacité réelle des opérations de sélection des composants est faible, c'est à dire si on élimine autant de "bons" composants que de "mauvais", toutes celles qui ont été faites se justifient (par exemple, pour les transistors et circuits intégrés, il faudrait que plus de 80% des déchets à ces essais soient artificiels pour que le procédé perde de son intérêt).
- le déverminage du module 29 aurait pu être remplacé de façon économique par cette sélection des diodes de puissance au stade du composant ;
- le taux de défaillance des composants " à la mise sous tension " doit être retenu comme critère pour décider s'il faut renforcer ou au contraire relâcher la sévérité des opérations de sélection en amont.
- un déverminage d'ensemble d'une vingtaine d'heures est efficace : la plupart des défauts constatés à ce stade auraient entrainé un défaut de jeunesse en exploitation ;

  par contre, il n'est pas utile de prolonger le déverminage: on fait alors apparaître, en plus de défaillances sans dou-

te liées à des défauts de jeunesse, trop de défaillances artificielles pour que le procédé soit justifiable dans le cas général ;

- le rodage au banc, sans contr[illegible]es climatiques, est intéressant pour se faire une idée valable de la fiabilité d'exploitation, mais en tant qu'outil de fiabilisation, il ne faudrait y faire passer systématiquemennt les équipements que si la MTBF sur un prélèvemennt est nettement inférieure à la MTBF objectif.
- enfin et surtout, une politique constante de haute fiabilité pour ce matériel donne de façon gratuite un excellent résultat à long terme : les réactions chez les fournisseurs de composants ont abouti à la fourniturede pièces de meilleure qualité et de meilleure fiabilité.

4 - CONCLUSION -

De l'ensemble des travaux qui viennent d'être décrits et en particulier de l'étude de "coût-efficacité" des méthodes de fiabilité appliquée à un radio-altimètre, on peut tirer quelques conclusions simples.

La plus grande conclusion est une conclusion de bon sens (et ce n'est pas décevant dans la mesure où le bon sens n'est pas évident): on ne fait pas de la"haute fiabilité" avec des moyens "artificiels"; il faut de "bons composants" et un "travail propre" pour les assembler. En effet, il serait illusoire de vouloir rattraper par des essais de déverminage ou autres une fabrication imparfaite avec de mauvais composants.

L'autre grande conclusion est que pour appliquer ces méthodes simples et s'assurer de leur efficacité, il faut intervenir à tous les stades de la vie de l'équipement : développement et utilisation de bons composants, analyse détaillée du projet par des calculs de fiabilité prévisionnelle, fabrication soignée, vérifiée et complétée par des déverminages et des essais de fiabilité judicieusement choisis, au niveau de leur durée et au niveau des contraintes appliquées.

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Ce texte est partiellement basé sur des travaux réalisés par TRT sous contrat STTA 7286087 et avec LMT sous contrat STTA 7481017.

Table 1

ESSAIS EN CONTRAINTES ECHELONNEES

Essais	Nombre	Conditions d'essais	Nombre de cycles d'essais ou contraintes échelonnées	Observations
Etanchéité	Totalité	Détection de fuites -par Hélium -par liquide	Les essais d'étanchéité pourront éventuellement être repris après une série d'essais mécaniques et climatiques	
Varations rapides de température	5	CCTU 01-01A par SB (Méthode A) -55°C +125°C	5 - 10-20-40	Mesures après chaque série de cycle.
Chocs thermiques	5	0 + 100°C CCTU 01-01 A par S.B (Méthode B)	5 - 10-20-40	Mesure après chaque série de cycle
Température	10	4 H de stockage à chaque température d'essai 2H de reprise	Température échelonnées 25°C 150°C 100°C 175°C 125°C 200°C au-delà, de 25°C en 25°C jusqu'à destruction	Mesure à la température de 25°C ±2°C après chaque reprise
Chocs	5	0,5 ms 0,2 ms	1500 - 2000 - 2500 - 3000 g	Mesure après chaque essai
Vibrations 1-Essais à g croissants	5	Balayage de 100 à 2000Hz aux accélérations successives 10-20-30g	1 cycle de durée de 15 minutes	
2-Cycles répétés	5	Balayage de 10 à 2000Hz à g constant (par exemple 20g)	Mesures après 20 cycles 30-40-50cycles	
Accéleration constante	5	CCTU 01-01 A	Mesures après 10000 g 15000 g - 20000 g et au-delà jusqu'à 100000 g	

Table 2

Sub-units	Influence percentages due to								
	R (%)	C (%)	Semi-C (%)	Cw.int (%)	Poten (%)	Magne (%)	Conne (%)	Divers (%)	% Total
Z1	0.6	2.3	94.3	0.0	0.0	2.7	0.2	0.0	14.3
Z2	0.0	0.0	99.1	0.0	0.0	0.0	0.9	0.0	6.0
Z3	4.9	4.4	30.4	57.0	1.7	1.0	0.6	0.0	3.5
Z4	1.2	0.8	75.3	21.4	1.2	0.0	0.1	0.0	10.1
Z5	1.5	0.8	64.2	32.5	0.4	0.3	0.1	0.0	15.4
Z6	2.0	0.7	30.0	66.1	1.0	0.0	0.1	0.1	12.7
Z7	2.4	1.7	94.1	0.0	0.0	1.7	0.2	0.0	8.5
Z8	1.4	0.8	72.4	23.2	2.0	0.0	0.1	0.0	9.3
Z9	2.4	7.2	48.2	37.8	0.0	0.5	0.1	3.8	7.6
Z10	0.0	0.0	0.0	0.0	0.0	0.0	0.1	94.2	12.0

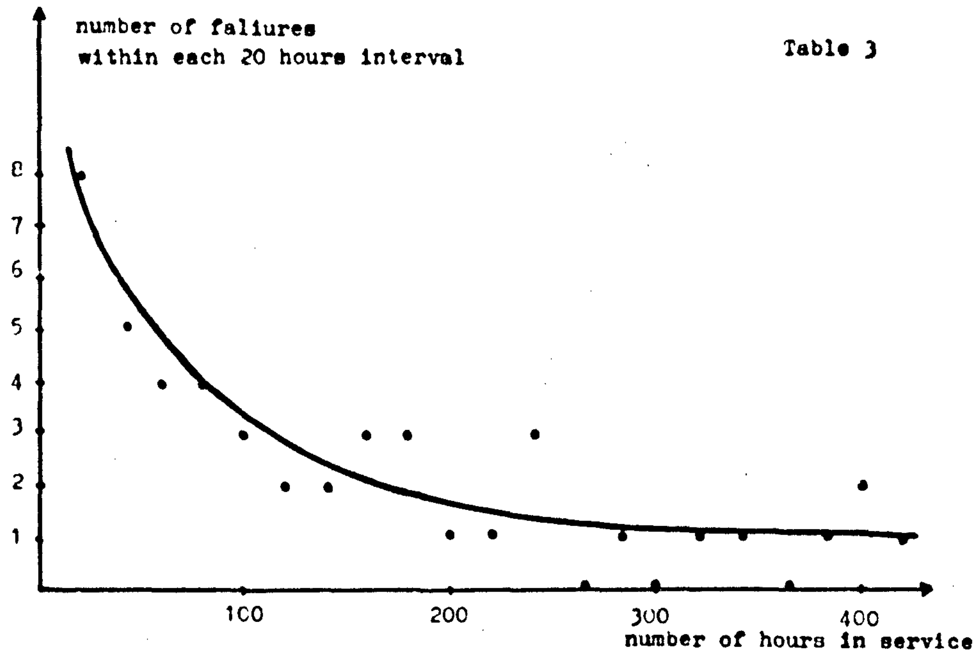

Table 3

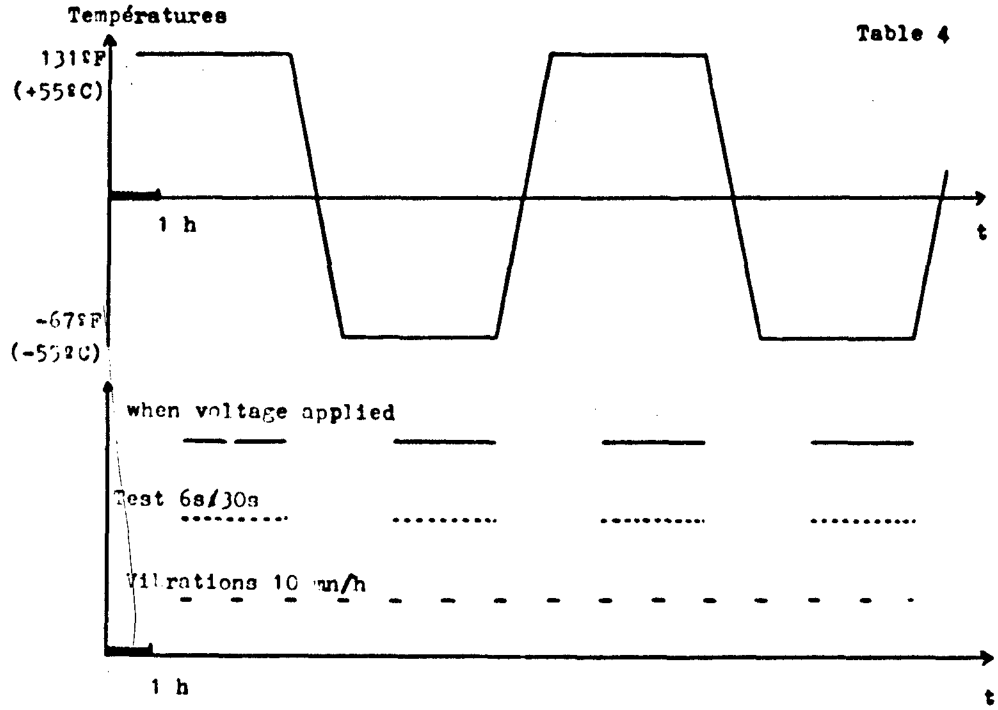

Table 4

Table 5

100 semiconductors	CCQ	components selection	applied voltage	whole equipment burn-in	warranty in operational phase	total
cost price	300	225	150	90	60	825
waste rate		23 %	2 %	0.6 %	0.2 %	(26 %)
process effectiveness eliminated component			85 % (burn-in of Z1 and Z9)	50 %	100 %	
mean cost of an eliminated component		10 à 25	90	300	300	

CASE HISTORY OF SOME HIGH RELIABILITY DESIGNS FOR AVIONIC SYSTEMS

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0. INTRODUCTION

To obtain high reliability equipment, it is necessary to use appropriate methods and specific techniques. At the "Service Technique des Télécommunications de l'Air" (STTA : Air Force Telecommunications Technical Department), the various phases of reliability development are conducted as follows :

- components : efforts are directed towards the achievement of manufacturing processes leading to high reliability devices.
- reliability prediction : appropriate calculations are carried out to analyze the stresses to which components are submitted and improve circuit design.
- reliability and burn-in tests : their purpose is to reveal early operation defects and systematic failures, as well as to give an estimation of reliability close to the operational value.
- reliability clauses : guaranteed reliability or contractual maintenance clauses ensure that the aim in view has been reached.

The above methods, which have been applied recently to avionics equipment developed under the sponsorship of STTA, will be first described and illustrated by applications to concrete cases ; then, we will present the main results of a study which aimed at analyzing the efficiency of such methods, from the "cost-reliability" standpoint, for a particular example. Finally, we will bring out the essential lessons learnt from the application of these methods to known equipment.

1. GENERAL POLICY

We will first give a description of the various methods used to obtain high reliability equipment.

1.1. Component Level

Reliability clauses including tests conducted under severe climatic and mechanical conditions are systematically introduced into new electronic component design and development contracts. An example of such tests is given in table 1.

The purpose of these tests is to bring out the possible causes of failure and to ensure that the manufacturing processes lead to high reliability devices.

As far as the manufacturing of a piece of equipment is concerned, the responsibility of purchasing components devolves obviously on the manufacturer ; however, the latter must give preference to "CCQ components" (CCQ : Contrôle Centralisé de Qualité - Centralized Quality Control), that is to say components whose quality is controlled by a national organization called "Service National de la Qualité" (SNQ : National Quality Department), or to those selected through a specific programme by the component manufacturer. However, the latter are more costly.

1.2. Reliability Prediction

When contracting for the design of new material or systems, STTA requests, as a rule, that reliability prediction calculations be carried out, for several reasons :

- such calculations require that the system be completely broken up into its constituent parts and imply a stress analysis [illegible] component, following the drawings [illegible] in the design department : therefore, this means additional checking.
- the first estimations obtained may lead to modifications for the improvement of results (selection of components, circuit design...).
- the results obtained can also be used as a basis for a maintenance programme.

As regards the selection of information, the following procedure is followed :

If satisfactory information on the use of a module under the same conditions as the item considered is available, this information should be used first.

Besides this possibility, failure rate data [illegible] can be used [illegible] 217, [illegible] a similar document published by the "Centre National d'Etudes des Télécommunications" (CNET : National Centre for Studies on Telecommunications) is recommended. When possible, the calculations derived from different sources should be [illegible] in order to check the sensitivity of the results.

1.3. Reliability Testing

These tests are conducted on prototype or mass-produced material. Their objective is to improve reliability by detecting systematic defects at a stage when it is still possible to remedy them from both technical and financial standpoints, and to give an estimate of reliability closer to the operational value.

Efforts are made to achieve, in the laboratory, climatic and mechanical environment conditions close to those prevailing under operational conditions.

The tests carried out are similar to those described in the specifications MIL 781 A or in the equivalent French specifications (CCT 190).

An example of the application of such tests to an airborne transponder (IFF) will be given later on.

1.4. Burn-in Phase

Burn-in consists in running the material, with or without stresses, prior to acceptance, in order to eliminate the early operational defects. This operation is very frequently performed by the manufacturer, either to have more chance of meeting the acceptance conditions, or to avoid making too many repairs during the period of warranty, or at the request of the technical service.

The duration of the burn-in period varies according to the manufacturer concerned and depends on the complexity of the material.

A test performed under thermal and mechanical stresses, lasting approximately 20 hours and prolonged up to 100 hours by a burn-in period (simple operation) seems to be efficient enough to remove early defects. However, it is extended by some manufacturers up to 200 or 350 hours. Specific burn-in examples will be presented further on.

1.5. Guaranteed reliability

In order to obtain high reliability equipment, a Guaranteed Reliability Clause must be added to the purchase contract. This most important problem will be discussed in another paper.

2. APPLICATION OF THE METHODS

In order to illustrate these general methods, we will describe their application to a radioaltimeter. This type of equipment is a good example because, on the one hand, its reliability is excellent (MTBF over 2000 hours) and, on the other, it is suited for a cost-efficiency analysis ; as a matter of fact, not only can the cost of reliability promotion not be disregarded in the calculation of the overall cost, but also an actual reliability "follow-up" has been set up at all the development and production stages, which constitutes a considerable source of information as well as the means of assessing the efficiency of these methods, as will be seen further on. The application of these methods to other material, in particular to IFF airborne transponders, will also be described, for the sake of illustration.

2.1. Description of the equipment

The reference equipment is the transmitting-receiving unit of a radio-altimeter.

This unit consists essentially of a solid-state, hyperfrequency, frequency-modulated generator (Z1 module), a homodyne receiver Z2 associated with an amplifier Z3 actuating a discriminator Z7. After identifying the signal received by an acquisition-tracking logic module (Z6), the discriminator signal actuates the modulator Z5 (therefore, closed-loop operation). Modules Z4 and Z8 transform the internal signals into usable altitude signals and the supply unit Z9 provides the overall system with the appropriate voltages. The complexity of the system can be defined by the following figures : 600 components, out of which 70 are transistors, 30 linear integrated circuits and 5 logic integrated circuits.

2.2. Reliability Prediction

Two methods were used for reliability prediction.

At the development stage, the maximum-minimum method described in document HDBK 217 A was used to predict a range of MTBF values while the study was still going on.

Once the final patterns have been selected, a second evaluation was carried out on the basis of the data provided by RADC 68. For this purpose, a stress analysis was performed for each component in order to make sure that the danger limits of use of these components had not been reached.

This second set of calculations revealed a 30 % increase in the MTBF over the first evaluation, and a different distribution of the percentages of influence of the various types of components, bringing out the prominent part played by solid-state component and integrated circuits (70 %) in the failure rate.

As indicated in table 2, the calculations also showed the distribution of reliability by module.

2.3. Selection of Components

Since reliability prediction calculations pointed out the importance of solid-state components, and experience demonstrated that diodes are generally good, a particular effort was devoted to transistors and integrated circuits. These were purchased following specific selection programmes carried out by the manufacturers whose reports reveal a rejection rate varying considerably from one batch to the next. The average percentage is 23 % of rejects in selection tests, with extreme values ranging from 3 to 70 %.

Apart from solid-state components, chemical capacitors and electromagnetic relays were carefully studied for their reliability. These two types of components were also aged artificially with voltage applied. In the case of chemical capacitors, for example, the selection criterion was the leakage current after ageing ; in that of relays, the criterion was correct operation.

As to the other components, whose influence on reliability is less important, as shown by the reliability prediction analysis, they were acquired according to lists approved by the military administrative services and by the governmental quality control organizations.

2.4. Burn-in

2.4.1. Radioaltimeter

For this radioaltimeter, burn-in operations were conducted on three levels :

a) After the wiring assembling phase, two modules are submitted to thermal cycle ageing for approximately 100 hours.
One of the modules, a hyperfrequency generator 21, must be stabilized while charged prior to final adjustment ; such stabilization plays an important part in the burn-in phase when it eliminates faulty UHF transistors and some ceramic capacitors.
The supply module, 29, has to be burnt-in separately and prior to being coated with varnish, in view of its high rejection rate.

b) Following assembling and adjustment, the complete packs are subjected to thermal cycle (- 40°C + 70°C) burn-in with rated voltage and vibrations applied, for approximately 100 hours.

c) Finally, the equipment is submitted to breaking-in for 200 hours, in the laboratory.

2.4.2. A burn-in test was conducted more recently on an airborne IFF transponder.
The purpose of the study was to carry out tests to determine the duration of the burn-in operation necessary to ensure optimum operational reliability from the very initial stage of operation of the equipment.
The following method was applied :
24 devices were sampled from the mass-produced items and submitted to tests for 800 hours, out of which 400 hours were in operation.
The test cycle was worked out on the basis of the reliability tests described in specifications MIL 781 A or CCT 190 : that is to say, a temperature cycle ranging from - 55°C to + 55°C, and vibrations ranging from 0 to 100 Hz, at 2g, applied for 10 minutes in every hour.
As far as equipment testing is concerned, the internal test of the transponder which was operated every 30 seconds, was used, and checks were made twice a day to detect the eventual performance degradation of the main functions.
An index card was made for each equipment.
Let us analyze the results obtained.
The overall equipments went through approximately 10, 000 hours of operation, and these tests led to two types of action :

a) On the one hand, plotting the failure rate curve as a function of time made it possible to (table 3) :

- bring out the first two portions of the "bath tub curve", typical of electronic equipments.
- estimate the MTBF prior to burn-in, according to the well-known rules of the confidence interval laws. The values obtained corresponded to the early operation results.
- determine the burn-in time necessary to reach the "bath tub bottom". As the curve was clearly characteristic, it appeared with evidence that the main early operation defects had been eliminated after 100 hours.
- estimate the MTBF after burn-in. It is demonstrated that the initial MTBF can be increased by 160% through burn-in.

b) On the other hand, the reduction of the data on the various types of failure revealed a few weak points in the equipment, mainly the malfunctioning of mechanical elements at low temperatures, and a few types of defective components. Possible remedies were considered, some of them extending as far as the complete remaking of certain circuits. A very substantial improvement of the MTBF can be expected after the application of the modifications to the equipment to be produced.
The technical lessons drawn from these tests suggest the following modifications : reinforcement of metallization in connection holes for double-sided circuits, and usefulness of selection tests for a type of integrated circuits. It is worth noting that the cost increase of the components selected from integrated circuit producing firms has not been reflected in the cost of the equipment ; it seems that it was counterbalanced by a reduction in the cost of the manufacturing, control and repair of circuit cards in the production process, where the number of failures was very high prior to circuit burn-in.
Such action proved to be very efficient, since no metallization failure occurred during the tests, and the reliability of integrated circuits was improved.

2.5. Reliability testing

Reliability tests in conformity with the specifications MIL 781 A or CCT 190 are conducted fairly often.

A particular application of these reliability tests to another type of airborne IFF transponder will be described.

One of the purposes of these reliability tests was to improve reliability as well as to get a better knowledge of the MTBF under actual operating conditions. Therefore, in order to approach as closely as possible to real mechanical and thermal conditions (ref. table 4), it was necessary to effect several adaptations of the test cycles described in the specifications MIL 781 A.

The main results of these tests are the following :

- comparison of the MTBFs obtained through predictive calculations and reliability tests, under actual operating conditions :
  - . through calculations (RADC) : 600 hours.
  - . through tests : 470 hours.
  - . under actual operating conditions : 660 hours.
- additional information was obtained :
  - . very strong influence of the temperature and vibration cycle variation law.
  - . determination of the optimum duration of the burn-in phase (30 hours in this particular case).
  - . sure knowledge of the equipment behaviour, which provides means of negotiating the Guaranteed Reliability Law.

Reliability tests conducted in laboratories are generally regarded by CTTA as very valuable ; at the prototype and pre-production stages, they provide the means of detecting reliability "errors" ; at the mass-production stage, they give a good approximation to the operational MTBF, which permits improved maintenance (calculation of replacements) and provides indispensable information for the introduction of a guaranteed reliability clause into a contract.

3. EFFECTIVENESS OF METHODS

3.1. General

As stated in the above chapter, achieving good reliability requires the application of methods at all levels : at the equipment design stage, in the selection of components, in the manufacturing methods chosen, as well as during tests of all types or when drawing up and applying a quality control policy ; therefore, each phase in the life of an electronic equipment provides opportunities for improving reliability through specification. To each action corresponds an accessible cost which the analytic accounting of the equipment manufacturing firm makes it possible to know, but, most of the time, it proves impossible to associate also each action with a given level of effectiveness.

This is due to the probabilistic nature of reliability - and of related quantities (MTBF, failure rate) - which makes it difficult to measure and to the shortage of analytical methods of a general nature.

A specific study was undertaken, its purpose was to derive from real data quantitative relations between the reliability improvement of an electronic equipment and the corresponding cost increase. These relations were to determine the "cost-effectiveness", so to speak, of the various means which can be implemented in the development of an electronic equipment, to improve reliability ; therefore these relations make it possible to choose the right weight, to give to each of these means in order to reach a set reliability objective as economically as possible. To give a concrete character to this study, it was applied to the radio-altimeter already mentioned.

3.2. Method Analysis Process

For the study considered the data collected on the radioaltimeter production line, which produced over one thousand pieces of equipment over three years, were used ; thus, a considerable amount of data was accumulated :

- data on failures occurring in the equipment or one of its sub-units in the course of breaking-in tests. As a first approximation, we will admit that the MTBF resulting from this estimation provides a sufficiently accurate idea of the operational reliability of the equipment, as was verified through other means.

- identification data on all the operations carried out on the production line since its inception (supplies, tests, control, etc.).

All the information available on 3000 operations was recorded on a data file including approximately 20, 000 blocks of 80 characters.

In order to appreciate the effectiveness of reliability improvement methods, all the resources provided by statistical and factorial analysis were resorted to.

Besides, the analysis of the effectiveness of reliability improvement operations was considerably facilitated by the quality of repairs at each stage : it is demonstrated by a first analysis that these operations do not affect markedly the subsequent life of the equipment and, therefore, that reliability improvement processes are followed by independent consequences as regards a given equipment.

3.3. <u>Critical review of methods</u>

The various actions described previously lead to a critical review at all levels :

<u>Critical review of the manufacturing record and of reliability prediction calculations</u>

First, reliability predictions can be controlled.

Solid-state components play an essential part in the long range reliability of the equipment ; however, integrated circuits also play a leading role, especially as, in this case, the reliability selection method is not very effective.

The distribution of failures is in rather good agreement with the predictions : as a matter of fact, modules 21, 26 and 29 are the most delicate, but, whereas the failures of 21 and 26 do not affect long-term reliability, a high failure rate of the power diodes in the supply module is the certain sign of probable fatigue and weakness in the near future.

<u>Critical review of component selection methods</u>

As far as chemical capacitors are concerned, ageing with monitoring of the leakage current proved efficient, especially as the long rest period which followed this ageing phase, prior to assembling and re-applying voltage, allowed many dubious elements to continue their evolution and to be eliminated. For this type of component, the action of ageing cycles is now well-known and a similar, but faster mode of selection can be contemplated.

As regards integrated circuits and field effect transistors, the selection method proved rather ineffective.

The batches which the manufacturer indicates as offering a higher rejection rate than the average during reliability improvement tests, also offer a higher mortality rate during the subsequent operations and under actual operating conditions. The reinforcement of reliability improvement tests and checks resulted, during these tests, in a higher rejection rate, although this was followed by no subsequent effect.

However, this selection may have had a beneficial impact : due to the considerable number of rejects in the course of reliability improvement testing, as well as to repeated complaints, the manufacturer delivered batches of a markedly better quality around the end of the production period.

As regards bipolar transistors, our statistical analysis does not enable us to draw any conclusions : in operation, as well as in the course of the manufacturing phase, the failure rate remains low and seems to show a thoroughly random character.

Critical review of burn-in [illegible]

. Burn-in was carried out on two modules : 21 (UHF generator) and 29 (supply). It is shown by analyses that :

These two modules behave quite differently : whereas burn-in seems effective on module 29, the result does not appear to be convincing as regards module 21, although ageing of the module with voltage applied is absolutely necessary before the final adjustment phase, to counteract the often destructive variation of transistor characteristics.

. As regards the burn-in of complete units, we note that almost half the failures occurring during the first 20 hours correspond to manufacturing faults which, in this case, are completely eliminated, without further consequences. Based on this, we can conclude that these first 20 hours of burn-in resulted in a 40 % reduction of the premature defects revealed in operation : therefore, these first 20 hours do play the burn-in role expected from the test.

The other defects detected during these initial hours of burn-in are of the same type as those detected later on during the test. The role of burn-in is not evident, except for inductances, chemical capacitors and power supply rectifier diodes.

As far as integrated circuits and field effect transistors are concerned, the failure rate during the test provides an indication of the quality of the batch.

It remains to draw conclusions on the overall effect of the test : have most failures which would have taken place in the early or late stage of operation been eliminated by this test ? If we analyze the various aspects, we can state that the effectiveness of the burn-in operation is unquestionable, but that, as a corollary, failures unrelated to reliability are induced when the burn-in is too rough, especially if it is prolonged beyond 20 hours.

Critical review of the industrial reliability regulating process

Two main feedback loops were supposed to give some stability to the quality and reliability of the finished product ; one was based on the qualimetry of the industrial control, and the other on the measurement of the MTBF during burn-in tests on the overall system. The analysis of this process revealed that the transfer function of the feedback loops was inappropriate, in particular because of the time constant.

As a matter of fact, an industrial check whose effects are felt too long after the production is ineffective if, in the interval of time between the detection of the early defects, the determination of their causes (defective instrumentation, inadequate staff) and the remedy, many equipments continue to be affected by the same faults.

As regards the reliability loop based on the results obtained during the burn-in phase, its short or long term regulating effect is non existent since the failure rate at this level is not representative of the material reliability.

3.4. Breakdown of Reliability Improvement Cost

The premium to be paid for the production of a highly reliable radio-altimeter, with the initial manufacturing process, was approximately 30 % of the cost of the equipment : the cost of component selection amounted to 15 % of this sum, as well as the cost of burn-in and checking operations.

For the sake of illustration, we can draw up a table of the cost-efficiency ratio of reliability improvement operations for active semiconductors whose failure rate is high in relation to the overall failure rate of the equipment. These active semiconductors are involved in two failures out of three.

On average, the approximation formula of the extra premium S which we paid to the supplier for the selection operations can be written as follows :

$$SN = 1\ Z + P/3$$

The efficiency analysis suggested a means of reducing appreciably the "reliability" budget, and, probably, of limiting it to an extra premium of the order of 10 %. As a matter of fact, the analysis reveals that, in spite of all precautions, the reliability of the equipment remains a direct function of the quality of the spare parts.

The procedure to be followed in order to achieve the best possible cost-reliability trade-off would be the following :

- even if the real effectiveness of the component selection operations is low, that is to say if "good" and "bad" components are eliminated in equal numbers, all the operations which were carried out are justified (for instance, in the case of transistors and integrated circuits, over 80 % of the rejects would have to be unjustified for the method to lose its interest).

- the burn-in of module 29 could have been replaced, with financial advantage, by this selection of power diodes at the component stage.

- the failure rate of the components with voltage applied should be retained as a criterion on which to base the decision for increasing, or, on the contrary, reducing, the strictness of the selection operations "upstream".

- an overall burn-in of 20 hours duration is efficient : most defects detected at that stage would have brought about failures in an early operation phase.

- on the other hand, it is not useful to prolong the burn-in phase, as besides failures probably related to initial defects, this reveals too many artificial failures for the method to be warrantable in general.

- breaking-in on the test bench, without any climatic stresses, is valuable insofar as it gives a good idea of operational reliability : however, all types of equipment should not be systematically submitted to such testing, unless the MTBF of a sample is markedly lower than the MTBF set as an objective.

- finally, and above all, a constant high reliability policy, for this material, yields excellent long term results, at no cost ; it has led to the production of better quality and higher reliability parts by component suppliers.

4. CONCLUSION

From the overall work described in this paper, and in particular from the "cost-efficiency" study conducted on reliability methods as applied to a radio-altimeter, we can draw a few simple conclusions.
The most essential conclusion is one of common sense (and this is not disappointing inasmuch as common sense is not evident) : "high reliability" cannot be achieved with artificial means ; "good components" and a "clean job" for assembling them are required. As a matter of fact, attempting to compensate a defective production including faulty components by burn-in tests would be erroneous.
Another most important conclusion can be drawn : to apply these simple methods and ensure their effectiveness, measures must be taken at all the stages of the equipment life : development and use of good components, detailed project analysis by means of reliability prediction calculations, careful manufacturing, controlled and complemented by judiciously selected burn-in and reliability testing as regards both service life and stresses.

This text is partly based on work performed by T.T under contract N° 72 60067 with S.T.T.A. and by L.[illegible].T. under contract N° 74 6[illegible]7 with S.T.T.A.

TABLE 1

STEP STRESS TESTS

TESTS	NUMBER OF SPECIMENS	TESTING CONDITIONS	NUMBER OF TEST CYCLES OR TESTS STEP STRESS	REMARKS
Tightness	Whole production	Leakage detection - by Helium - by liquid	Tightness tests may be eventually resumed after a series of mechanical and climatic tests	
Rapid temperature variations	5	CCTU 0[illegible]-01 A by 5 B (A Method) - 55°C + 125°C	5 - 10-20-40	Measurements after each cycle series
High thermal stresses	5	0 + 100°C CCTU 0[illegible]-01 A by 5.B. (B Method)	5 - 10-20-40	Measurements after each cycle series
Temperature	[illegible]	4 hrs. of storage at each test temperature [illegible] of recovery	Progressively increasing temperatures : [illegible]5°C 175°C 100°C 125°C 200°C 150°C Beyond, [illegible] 25°C until destruction.	Measurements at 25°C ± 2°C after each recovery phase
Impact	5	0.5 [illegible] 0.2 [illegible]	[illegible] - [illegible] - 2500 - 5000 [illegible]	Measurements after each test
Vibrations : [illegible] - Test at [illegible] [illegible]	5	[illegible] of [illegible] 2000 [illegible] [illegible] [illegible] 10-20-30 [illegible]	[illegible] of 5 minute duration	
[illegible]	5	[illegible] 2000 [illegible] (5 [illegible])	Measurement after [illegible] 30-40-50 cycles	
Constant acceleration	5	CCTU 0[illegible]-01 A T[illegible] 25 A	Measurements after 10,000 g - 15,000 g 20,000 g and beyond up to 100,000 g	

Reliability Testing of Electronic Parts

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ABSTRACT:

A survey of the environmental, physical and electrical tests, which are necessary to establish the reliability of electronic parts, is given. Special accent is placed on the testing of semiconductors. All the tests are described together with the failure they can detect in parts. Within these three categories of tests, nondestructive and destructive ones are distinguished. Although most popular tests are mentioned, special emphasis is placed on tests not so widely used yet, such as high stress tests, accoustical particle detection, thermal mapping by means of liquid crystals and the test of input protection circuits of MOS IC's. The need for visual inspection as a means of improving the quality of components is discussed. Product analysis as a means of evaluation of the parts manufacturers capability is described in detail.

1. INTRODUCTION

The purpose of testing is to determine the
compatibility
- of materials within the component
- of circuit parameters
- of components with processes of the user
- of components with the anticipated environments [1]

The properties of materials must be tested by mechanical, chemical, electrical and thermal methods. It is most important that the test methods deliver reproducible test results. Therefore all the tests should be performed to well established standards. Besides, the environmental conditions for the tests must be given, for instance relative humidity for resistance measurements or atmospheric pressure for dieelectric breakdown measurements. The basic parts of a test are

- the test conditions
- the response during the test
- the measurements after the test

During the tests the processes may be reversible or non-reversible. The most important non-reversible process is aging.

Since it is not possible to predict a definite parameter, it is necessary to give confidence levels with which a certain percentage of measured parameters will fall in a definite category. All tests can be distinguished into two major groups, which are used to determine the quality of electronic components, namely nondestructive and destructive tests. Within these groups again one can separate environmental, physical and electrical tests. The following presentation is going to follow this general outline. Because of the importance of these two categories, however, two separate paragraphs are dedicated to life testing of electronic parts and the constructional analysis of technologies.

1.1. LIFE TESTING OF ELECTRONIC PARTS

Lifetime testing of electronic parts is performed at constant temperature. Tests are made at high temperature to get acceleration of failure mechanisms. In addition to high temperature electrical stress, such as voltage or current, is also used, which further enhances the sooner occurence of failures. One can thus usually distinguish two kinds of lifetime tests

- storage life time
- operating life time (elevated temperature plus voltage, current, power stress)

A very effective test is the high temperature reverse-bias test. The result of lifetime measurements are usually given as mean time to failure in hours or as failure rate in %/1000 h for a certain confidence level. Table I gives for example the results of lifetime tests for C-MOS integrated circuits of several manufacturers [3, 4].

Table I: Failure Rates of C-MOS Circuits of Several Manufacturers

LIFE TIME DATA OF SERIES 4000 C-MOS

FAILURE RATE in % / 1000h (60% C.L.) at 55°C and 10 V

TYPE	[illegible]		MOTOROLA		RCA		[illegible]	
IC PACKAGE	% / 1000 h	DEVICE HRS	% / 1000h	DEVICE HRS	% / 1000h	DEVICE HRS	% / 1000 h	DEVICE HRS
CERAMIC AL			0 0102	3 225 190	0.028	3 560 000	0.012	1 166 388
CERAMIC CL								
PLASTIC CP	0 064	24 046 685	0.02	34 763 042	0.06	3 350 000		

ACCELERATION FACTORS

200°C hours x 10.7 = equivalent 55°C hours
150°C " x 8.0
125°C " x 6.0
85°C " x 2.5
25°C " x 0.37

[illegible]: ALL TESTS AT 125°C and 150°C operating tests
150°C storage life

Motorola: 85°C for CP and CL
125°C for AL

RCA: at 85°C

Most important in lifetime test comparisons is that the tests should be conducted for the same amount of device hours. In calculations one failure after the test-time has to be assumed, so even for zero failures at that time the failure rate is high. The more device hours there are, the better the actual failure rate can be determined. In table I also some acceleration factors are given by means of which the equivalent of 55 °C failure rate can be calculated [2]. This is also indicated by the number of failures vs. time curve of Fig. 1.

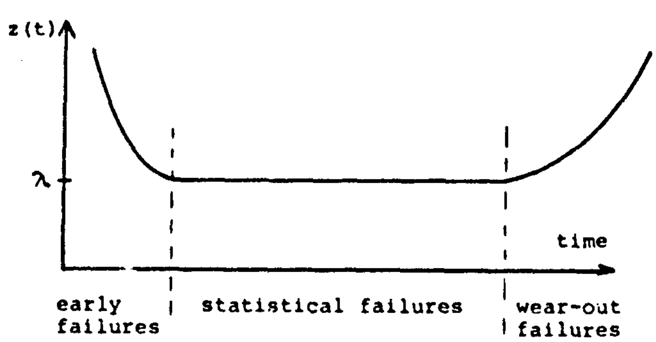


Fig. 1: "Bathtub" Curve of Failures vs. Time

Only in the flat part of the curve a component should be operated. Burn-in should eliminate the parts during the high mortality range.

1.2. ENVIRONMENTAL TESTS

In all the environmental tests the stress applied is so high, such as not to weaken good devices but to show weak devices. The stresses that must be applied to components to detect failures are however much higher than those that can be used on an equipment level. So unless the testing of the components has been done before assembly, there mostly is no way to test for weak devices after assembly.

1.2.1. THERMAL TESTS

There are three types of thermal tests

- tests at constant temperature
- thermal cycles
- thermal shock

1.2.1.1. TESTS AT CONSTANT TEMPERATURE

The electrical parameters of electronic parts stabilize after storage for some time at high temperatures. This process is called burn-in. Sometimes this test is combined with voltage or power stress. Burn-in tests are useful for determining

- paramter drift failures in both active and passive devices
- inversion and channelling in semiconductors
- IC metalization defects (scratches, discontinuities at steps in oxide)
- pinholes in the oxide
- contamination (moisture and other)

Because of the stabilizing effect of high temperature, these thermal tests at constant temperature are performed before mechanical and other thermal tests. Lifetime measurements are also performed at constant temperature as indicated above.

1.2.1.2. THERMAL CYCLES AND THERMAL SHOCK

During temperature cycle and temperature shock tests the temperature of an electronic component is changed between temperature extremes. With thermal cycles the temperature change is performed slowly, whereas with thermal shock the temperature of the components is changed rapidly, mostly by means of transfer between liquids which are held at temperature extremes. The maximum and minimum temperatures are chosen so that they have no degradation of good IC's as a consequence. The changes in parameters and the failures produced during temperature cycling are caused primarily by differences in thermal expansion coefficients and by evaporation, condensation and freezing of moisture or other contaminants inside the package.

Thermal shock is a much more severe test than thermal cycles. The changes in characteristics and the damage during thermal shock are a consequence of the rapid change in dimensions.

These thermal tests serve to show the following failures:

- cracking of embedding and encapsulating components
- rupture of conductors or insulators
- weak lead bonds
- package defects
- metalization defects
- incompatibility of coeffic:ants of thermal expansion
- bad chip bonds

Table II gives the results of environmental tests on C-MOS devices based on the manufacturers information [3, 4, 5, 6].

Table II: Environmental Tests of C-MOS Circuits of Several Manufacturers

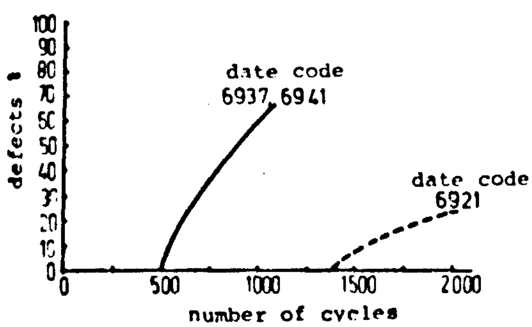
Environmental Tests Comparison of Manufactures

MIL STD 883	TEXAS			PLASTIC MOTOROLA			RCA			SSS		
	Device Cycles	Number Tested	Rejects	Device Cycles	Number Tested	Rejects	Device Cycles	Number Tested	Rejects	Device Cycles	Number Tested	Rejects
Method 1011 Condition A Thermal Shock 0°C + 100°C	100	100	0	1.980	44	0	6.310	862	5	100	100	0
Method 1010 Condition C Temp. Cycle -65°C +150°C	1.000	50	0	14.400	1.176	1	6.310	862	5	60.500	60	0

1.2.1.3. HIGH STRESS TESTS

As already indicated in the paragraph on tests at constant temperature, sometimes higher stresses are used to come as soon as possible to information concerning the quality of an electronic component. Stress tests have already been very important in the past, but will gain importance with LSI testing, because the number of components of one type produced may not be as high as with conventional devices. Therefore the statistics of lifetime tests are not as good also. Stress tests also serve the purpose of determining the maximum rating of a component and to determine the safety margins which are existing at specified operating conditions. Stress tests of different lots can very fast indicate process charges which can influence the reliability of a component. Fig. 2 shows a typical example of this [7].

Fig. 2: Percentage of Failures after a Number of Stress Cycles



The stress used was thermal shock by alternate immersion into liquid baths of -65 °C and 250 °C (dwell time in the bath 90 s at -65 °C + transfer time of 5 sec + dwell time in the bath at 250 °C = 1 cycle). One can clearly see that more recent circuits of the manufacturer (code 69 37 means 37th week of 1969) show a much sooner failure than formerly produced ones. With the help of this test manufacturing problems can be detected and solved much sooner or the user can switch to another manufacturer if he detects failures.

1.2.2. MECHANICAL TESTS

Mechanical tests are performed to show components with bad mechanical properties. Three types of stress can be distinguished

- vibration
- constant acceleration
- mechanical shock

These tests are performed after the thermal tests to detect components weakened by these tests.

1.2.2.1. MECHANICAL VIBRATION

The vibration test is used to determine the effects of vibration on components and it is very important to select an individual vibration level that is suitable for each component. Very important is the determination of critical resonant frequencies. Mostly the vibration met in the application is not of a sine nature, but records of actual vibration may be used to copy natural avionic or rocket environment. In monitored vibration the electrical performance is checked during vibration, for instance for shorts due to foreign particles in the component.

1.2.2.2. MECHANICAL SHOCK

A short pulse of high acceleration (up to 50 000 g) is used to test the response of devices to severe shocks as a consequence of drops or abrupt changes in motion produced by rough handling or transportation. This test is cheap and in IC's is used to detect bad lead dressing, bonds and package defects.

1.2.2.3. CONSTANT ACCELERATION

High constant acceleration centrifuge tests up to 40 000 g are used for components (IC's) to detect failures in contacts, solders, and to show weak bonds (perhaps due to purple plague) and bad lead dressing. Fig. 3 shows a bond weakened by purple plague lifted after acceleration tests. This will be shown in more detail in section 2.1. (Figures 14,15).

1.3. PHYSICAL TESTS

1.3.1. LEAK TESTS

Leak tests are made to test the hermeticity of components. Hermeticity is important to keep contaminants out of the component. It is also important because it can give an indication of the amount of outgassing to be expected. This is, however, described in more detail in the section on destructive tests, which barometric pressure tests can be.

Usually packages are said to fail if the leakage rates are higher than 10^{-8} cm ^{3}/sec. The limited range of measuring of each test method makes the use of different methods necessary. Gross leaks can be detected by means of the penetrant dye test. The part is immersed in a dye. This is a destructive test because the part has to be cross-sectioned to determine where the dye has penetrated. Mostly used for gross leak tests is the fluorocarbon type test [8, 10]. Fluorocarbons cause no corrosion or contamination. The component is immersed into a bath of fluorocarbon at, for instance, 125 ^{o}C and under a microscope of small magnification one looks for bubbles coming from the component with a leak. This method can show leaks up to 10^{-3} cm ^{3}/sec.

A more sophisticated test of this type makes use of two types of fluorocarbons with different boiling temperatures. The component is first put into a pressure chamber into which after evacuating a low boiling fluorocarbon is brought. The liquid is under high pressure and penetrates into any leaks. The component is then immersed into a bath of a higher boiling fluorocarbon liquid. Upon heating, first the low boiling liquid in the part evaporates and the gas escapes through the leak which is indicated by bubbles in the second liquid. This test shows leaks up to 10^{-5} cm ^{3}/sec.

Fine leaks are detected by means of the Helium leak test [9]. In the Helium leak test the component is brought into a chamber pressurized by Helium, so that Halium is pressed into a possible leak. Then it is brought into the vacuum chamber of a mass spectrometer which detects the Helium coming out of a leak. Leak rates of 10^{-6} cm ^{3}/sec to 10^{-10} cm ^{3}/sec can be detected.

With the radioisotope fine leak test, instead of the Helium a radioactive gas is used. The radioactive gas escaping from the leak can then be detected. The test is effective in a range between 10^{-8} to 10^{-12} cm ^{3}/sec.

1.3.2. X-RAY TESTS

X-ray tests of components can be performed in a static and a dynamic way. An X-ray photograph of the component can be taken and then be investigated under the microscope. In the dynamic mode an X-ray TV system is used which can be used to show the component as it is moving on a vibration table and thus perhaps show a foreign particle moving inside a relay or an IC can. The X-ray method is not very effective for elements as close together in the periodic system as silicon and aluminium but can be readily applied to Au-Si systems. The X-ray test can show

- foreign particles in the component or the case
- bad conductor or lead dressing
- relay contacts
- double lead bonds or voids in chip-bonds of IC's
- bad positioning of elements such as bonds not properly placed
- voids in encapsulants
- open leads in encapsulated coils or transformers

1.3.3. ACCOUSTICAL PARTICLE DETECTION

A vibration shaker can be used to bounce foreign particles around in the package of a component such as a relay. Loose Particle Detectors, as they are called, are commercially available and detect particles by the ultrasonic emissions produced by the particles as they bounce around in the vibrated package. A transducer is used to detect the ultrasonic emission and after amplification the signal can be monitored on an oscilloscope [11, 12]. Particles, having a mass as low as 0,1 μg, can be detected. The detection efficiency, however, increases with increasing size of the particles. For frequencies ranging from 20 - 3000 Hz and at 10 g's the dependence of detection efficiency on particle size is given in table III [11]:

Table III: Dependence of Detection Efficiency of Foreign Particles on Particle Size

particle size inch	% detected
0,002	40 %
0,003	85 %
0,004	100 %

1.3.4. THERMAL MAPPING

In most of the cases the temperatures of components have to be determined under actual operating conditions to determine the rating of the part. Thermocouples can be used in great number or several successive tests have to be made. Thermochrome crayons, which irreversibly change the colour at a specific temperature, are not as accurate but can in most cases of thermal design be used. Stickers are also available, showing the maximum temperature obtained. Above methods have lower spatial resolution and can only be used for bigger parts. The infrared microscope can be used for the determination of temperature distributions on parts or within IC's [13]. This method of thermal mapping is very effective in showing hot spots due to manufacturing or packaging faults. Like the following method it can be performed before capping the component.

A new, very cheap and effective method is thermal mapping by means of liquid crystals. These liquid crystals change the colour according to the temperature of the component, they are coated onto in a reproducible way if observed under a fixed angle. The background has to be blacked as any light reflected there serves to decrease the contrast. The colour change is reversible.

Table IV: Characteristics of Some Temperature Measuring Methods

	Temp. Accuracy	Spatial resolution	Temp. Range	Cost
Thermocouples	0,1 °C	1 mil	$\lessapprox$ 2000 °C	$1,000
Infrared	0,5 °C	0,5 mil		$10,000
Liquid Crystals	0,1 °C	1 mil	-20 °C to +200 °C	$1/g

Table IV shows the thermal and spatial resolution of several temperature measuring methods compared to the liquid X-tal method. The method is very well suited for the IC and hybrid technologies and even P.C. boards. Fig. 4 shows the calibration curve of a liquid crystal [14].

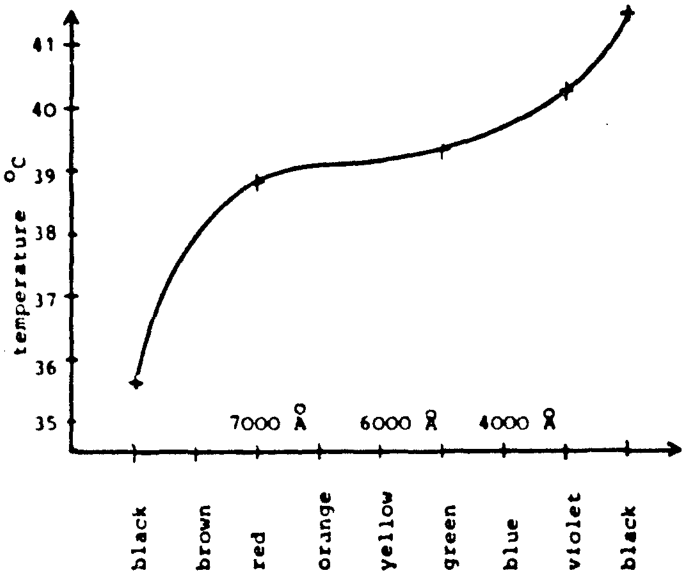


Fig. 4: Dependence of Liquid Crystal Colour on Temperature

Fig. 5, shows the failure rate of a resistor versus the surface temperature [15] and demonstrates the need for knowledge of the temperature. The liquid X-tal method by itself is not a destructive test, but of course in an IC the cleaning process can be deteriorating to some extent.

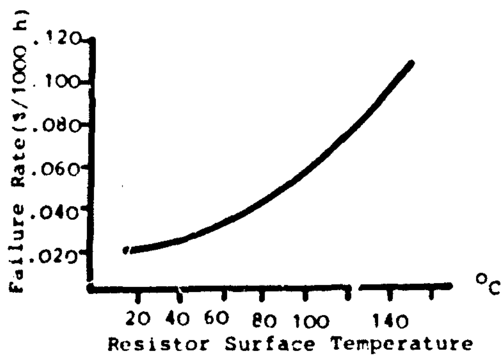


Fig. 5: Failure Rate of Resistor as a Function of Surface Temperature

1.3.5. VISUAL TESTS

The optical microscope can be used before capping the component to perform precap visual inspection. Even if the optical microscope is not as good with respect to resolution and depth of focus as the SEM, it has one advantage, namely that of colour. The colour information gives a high contrast between different parts in a component and, for instance, makes possible the determination of the thickness and homogeneity of oxides. The failures detectable with the optical microscope include

- foreign particles
- contamination and corrosion
- coating defects
- package and lead defects
- metalization defects such as scratches, holes, bridging in IC's
- bad lead bonds, double bonds, misplaced or cracked chips and wrong mask alignment in IC's

If, however, one wants to detect discontinuities in metalizations over steps in the oxide or look closer at bonds, then one has to use the SEM. Fig. 6 shows a chip where cracks extend into the active regions and which therefore is a reject. Fig. 7 shows a case where visual inspection is possible even with packaged devices. This picture shows a Charge-Coupled-Device image sensor, which of course has to have a window for the focused image. Fig. 8 shows the CCD device with the maximum magnification possible due to the low working distance of high power objectives.

1.3.6. SEM TESTS

Investigation of semiconductors with the Scanning Electron Microscope (SEM) is before packaging suggested as a means of checking the metalization of mission critical parts [16]. This however, should only be done on a sample basis because testing with the SEM can be a destructive test as shown by E. + G. Ress [17]. Radiation damage as a result of the electron bombardment can lead to threshold voltage shifts in MOS transistors. The negative rest gas ions are accelerated towards the scanned sample and cause contamination of the sample surface. So only in a limited way the SEM inspection can be considered as a nondestructive test.

1.4. ELECTRICAL TESTS

The field of electrical tests is so wide that it cannot be covered totally in a survey like this. Therefore I would like to pick out just a few tests for illustration of the complex.

1.4.1. INSULATION RESISTANCE

Even if the insulation resistance of capacitors, p.c. boards is very high, it may be the limiting factor in the design of circuits with high input impedance. This example shows very well that good care has to be taken to define the conditions of a test. For high insulation resistances during measurement the relative humidity of the atmosphere must be monitored because this can have a drastic influence on the measured value. Excessive leakage can lead to heating of insulators or to unwanted DC feedback loops.

1.4.2. FUNCTIONAL TESTS OF COMPONENTS

Functional tests are used mostly together with IC's to determine whether the circuit performs a specified function as a consequence of applied input patterns.

The logic output of the device under test (DUT) is compared either with the output of a reference IC or to a pattern generated in a computer. Only the sequence of "1" or "0" on the outputs is usually compared, but absolute measurements of the DUT levels can be made by comparing the output amplitudes to voltages set by means of adjustable power supplies. Functional tests are also the checking of the operation of a relay or switch.

1.4.3. PARAMETRIC TESTS OF COMPONENTS

As an example for parametric tests, those of IC's will be described as the most complicated type of parametric testing. Usually the parametric testing of semiconductors is performed in testers having the capability to test many parameters successively by the same tester. This is necessary to save testing time.

For failure analysis and incoming inspection simple manual testers are mostly used which are basically go-no-go testers but with a capability to determine a failed parameter. The average tester for static parameters is usually much cheaper than the testers of dynamic characteristics. So in that field specially designed separate testers are quite popular. One problem frequently encountered in failure analysis tests and in incoming inspection is that of the great variety of components that have to be tested. In the case of the component manufacturer the high volume may make the use of special adapters for testers feasible, but for low volume testing the testers should be easily adaptable to other part types. Best of all of course, is a computer-operated tester which also allows easy data logging and where only the software has to be changed. But the high price of these instruments is again not justified for low volume testing.

The details of which parameters have to be checked will not be covered here because this is different for each component. Just a few problems associated with the testing of higher complexity LSI circuits shall follow.

It has been shown, that in order to predict later failures, the method of pin-to-pin tests is most effective [18]. There are no problems performing these pin-to-pin tests on SSI and MSI circuits. But with LSI circuits a problem exists. For a circuit with n inputs the maximum amount of different states is 2^n (no memories or counters inside the circuits). The worst case for 2^n states is that one half is in the "0" state and the other half in the "1" state. In order to switch each "0" state to "1" and each "1" to a "0" $2^n/2 \times 2^n/2 \times 2 + 1$ switching cycles are necessary to arrive at the initial state. For a circuit with 15 inputs about 10^9 different tests would be necessary. With a time/test of 1 μsec the total testing time would be 16,6 min. So with LSI circuits only a few meaningful tests can be performed and the reliability of the circuits also ensured by performing scrutinous inspections during the manufacturing of the IC and by doing the constructional analysis of the technology as lateron described.

2. DESTRUCTIVE TESTS

2.1. EVALUATION OF THE MANUFACTURER'S CAPABILITY

For mission critical parts it is very important that the quality of the parts be ascertained. This should be done by taking samples of one lot and performing a quality analysis. The procedure would be almost the same as for failure analysis; specifications for the performance of failure analysis are available [19].

First of all, the DC and AC parameters should be verified before and after additional environmental tests as given in the specification. Decapping should then be done. For reference it is best to always check at least two devices. The die should be closely examined with an optical microscope first and important dimensions determined [20]. These values are important for the evaluation of the reliability and reproducibility of the circuit and can also be used to get information on the industry standard. All the possible failures described above can be detected in the optical microscope. The general outline to follow, including forms to be used for the evaluation recording, is given by L. Hartley [20].

Fig. 9 shows a sample of a non-uniform oxide shown by a change in the colour of the oxide. Next the metalization of the device should be checked for discontinuities at steps in the oxide. Fig. 10 shown a contact window where the Aluminium has been too deeply alloyed into the window. Fig. 11 shows some of the protective phosphosilicate glass missing which protects the Al-metalization and this might be due to too much etching or contamination, because part of the Al at the bonding pad also has been etched away. SEM pictures also can show the control the manufacturer has on his bonds. Fig. 12 shows a good lead bond. Fig. 13 on the contrary shows deep pits in the surface of the bond, the tool was worn out. Besides evidently too much pressure was used during bonding because the heel of the bond is very thin. Fig. 14 shows purple plague on the bond lifted during the centrifuge test (also see Fig. 3). Fig. 15 shows the bond remaining in more detail. By means of the microprobe add-on to the SEM, contaminations on top of IC's can be identified or shorts traced to material transport. Voltage contrast or electron-beam-induced current pictures can show opens in a metalization or shorts of junctions [17].

In order to determine junction depths, diffusion depths and bond profiles cross-sectioning should be performed and the diffusions made visible by colouring them either by depositioning of copper or by etching. Interference fringes can be counted in monochromatic light to determine the dimensions of interest (i.e. oxide thickness).

This kind of evaluation is invaluable in determining the quality of components and should be used to complement any other testing of the reliability of electronic components.

2.2. DESTRUCTIVE ENVIRONMENTAL TESTS

2.2.1. SALT SPRAY

In the salt spray test a fine mist of salt solution is sprayed onto the component. This test is an accelerated laboratory corrosion test simulating seacost atmospheres. There is however, no direct correlation between resistance to salt spray and resistance to corrosion in other environments [1]. Even though the prediction of absolute corrosion resistance is very difficult, from the result of this test a relative information can be obtained concerning the uniformity and thickness of protective coatings. Also as a method of checking the homogeneity of a coating process this test is valuable by comparing the tests to former results. Of course this corrosion-causing test is a destructive one.

2.2.2. HUMIDITY TESTS

Usually humidity tests are accelerated tests performed at high humidity and high temperature. An example is the test performed on plastic IC's described in the previous paper [21]. There in addition a bias was used.

The moisture penetrates through any leaks and through plastic materials. Absorption of moisture can result in swelling of that material that may cause rupture to bonding wires, metalizations and may also cause loss of mechanical strength. In some cases also the immersion of components into liquids such as salt water may be used as a test of the hermeticity of a seal. Because of the penetration of humidity this is a destructive test.

2.2.3. BAROMETRIC PRESSURE TESTS

This test is performed to simulate operation in aircrafts at high altitudes or satellites in the transfer phase to their orbit. The purpose is to test the resistance of sealants to pressure differences that exist in high altitudes. Besides, lower con-

vection cooling may cause thermal problems. The breakdown voltage of air is reduced in high altitudes. Due to outgassing, especially in higher flying spacecrafts but also in aircraft corona, discharges and even complete electrical breakdown may result. Also because of more arcing the lifetime of electrical contacts such as in switches and relays may be reduced.

2.2.4. FLAMMABILITY

Resistance to burning is very important for the safety of both, air- and spacecrafts. Primarily the ability of a component to support combustion is tested. For flammability tests the heat of the flame, the volume and surface of the component, time of exposure to the flame have to be known. The flammability degree is determined by the following parameters [1]

- the time until the fire extinguishes after application of a flame
- does a part burn violently
- does an explosive type fire occur
- is the spreading of fire on surface of larger parts inhibited

Besides this support of combustion, it is very important that corona discharge on, or heating of a component does not start a fire on the part.

2.2.5. RESISTANCE TO SOLVENTS

This test is especially important for certain plastic-coated components such as styroflex capacitors which by certain solvents can be harmed considerably. In ultrasonic cleaning baths only such solvents can be used which do not do harm to the encapsulating plastic. A further purpose of this test is to make sure that markings of components will not become illegible.

2.3. PHYSICAL TESTS

2.3.1. SOLDERABILITY AND RESISTANCE TO SOLDERING HEAT

This test is based on the ability of wires and components to be wetted by a coat of solder. Thus the coating of the component is checked. In the test accelerated aging simulating storage of at least 6 months is somestimes included. Most important it is in this connection to verify that at the suggested mounting distances no harm is done to the component during soldering.

2.3.2. TERMINAL STRENGTH

This test shows whether the terminals of a component, the leads of an IC can withstand the mechanical stresses exerted on it by installation in or removal from circuits. For different types of terminals different procedures are necessary. Radial, axial or tension pulls, twisting or bending forces are applied. After the application of the stresses, investigation with the microscope for breaking of seals, cracking, mechanical distortion has to be made. Electrical measurements can show interruptions or, for instance, resistance changes in a resistor.

An example shows how important this terminal strength test is. It was noted that the leads of IC's for a space mission just all came locse. Further investigation showed that the manufacturer had a problem. Traces of the etchant used to etch the oxide off the Kovar feed-throughs before gold plating them, was trapped in microcracks of the glass insulator. Lateron, as humidity washed out the etch, it attacked the leads and they finally simply fell off. Tests by the manufacturer could not have shown this defect because only after some time the etchant had weakened the leads. This experience stresser the need for incoming inspection and quality evaluation as described above.

2.4. DESTRUCTIVE ELECTRICAL TESTS

Some electrical tests are by their very nature destructive tests. As example dielectric breakdown and the test of the input protection circuits of MOS circuits are given.

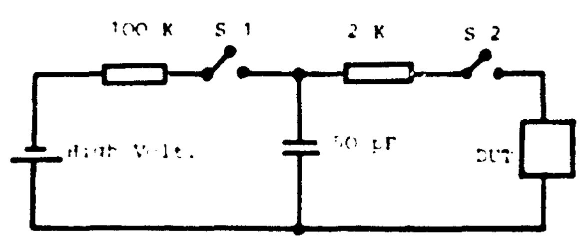
2.4.1. VOLTAGE BREAKDOWN IN DIELECTRICS

This test may be used to make sure that a component can work safely at its rated maximum voltage. The test however, can also be used to show how far away from actual insulation breakdown or corona discharge the rated value is. It then is a destructive test.

2.4.2. TEST OF INPUT PROTECTION CIRCUIT OF MOS IC's

As shown previously, the percentage of failure in MOS circuits due to overvoltage at the input, is quite high [21]. Figures 16 and 17 show the input protection of a C-MOS Silicon-on-Shapphire (SOS) inverter circuit, which consists of a MOS transistor with a low breakdown voltage connected from gate to source. Other manufacturers use the three diode circuit [21] which seems more effective. But in order to determine the efficiency of the protection circuit a test is suggested which tests out of one lot a few samples for the maximum voltage they can withstand at the input. A test circuit as shown in Fig. 18 is used.

Fig. 18: Test Circuit for MOS Input Protection



A variable voltage power supply charges a capacitor to the predetermined voltage as S1 is closed and then S1 is opened and S2 closed to apply the voltage to the input of the device under test. The protection circuit then has to discharge the capacitor before dielectric breakdown of the MOS gate oxide occurs. C=50 pF and R=2K simulate the capacity and the series resistance of the human body because that is how most of the static is applied. The test can be performed to check whether the sample IC's withstand a certain voltage negotiated with the manufacturer or the voltage can be increased until breakdown occurs to determine the safety margin present in the actual rating. This type of test is to be included in future GfW specifications of MOS devices.

CONCLUSION:

Concluding the need of reliability testing at the component level shall be stressed again. W.A. MacCrehan jr. has, as published [22] , found the following figures for the

relative cost of finding a defective part

- part screening = 1
- black box assembly = 3
- system (several black boxes) = 8

I think this demonstrates very well the need for reliability testing of components even though testing also adds to the costs.

ACKNOWLEDGEMENT:

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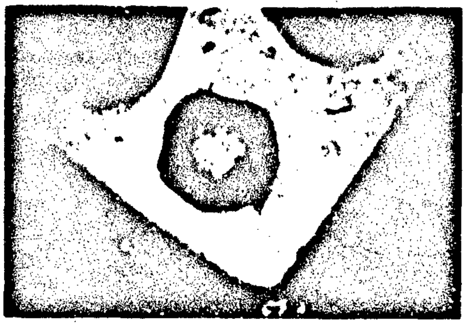

Fig. 3: Bond lifted after acceleration test

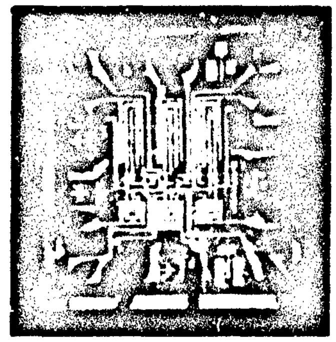

Fig. 6: CD4007 chip where cracks extend into active regions (50x)

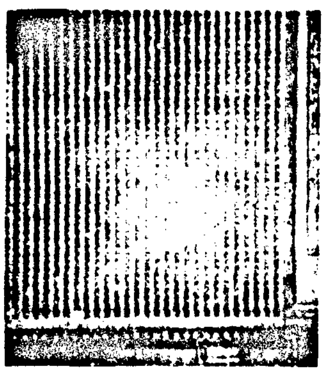

Fig. 7: CCD201BDC Image sensor as viewed through window (50x)

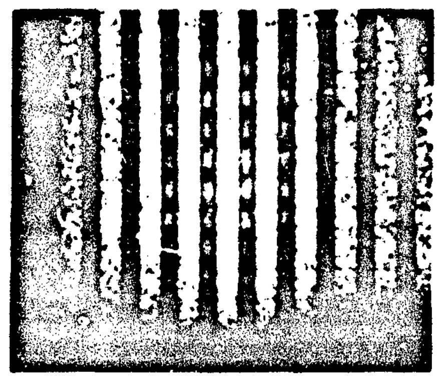

Fig. 8: CCD201BDC Image sensor viewed through window (200x)

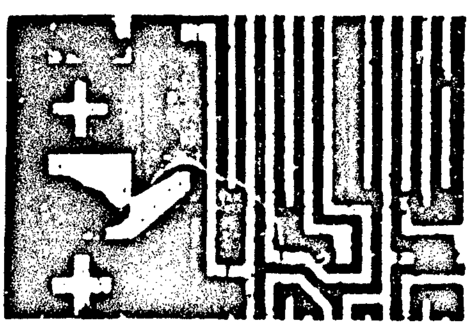

Fig. 9: Nonuniform oxide shown as discolouring in colour photograph, as patches in black and white (arrow points at defect)

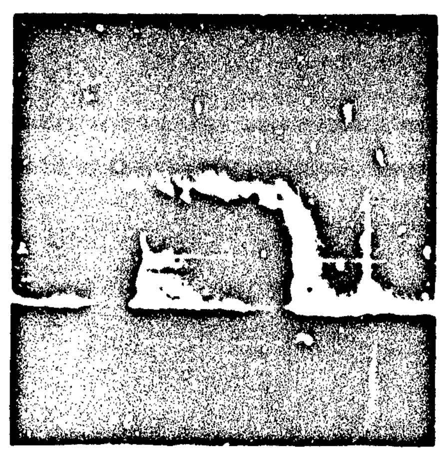

Fig.10: Metalization alloyed too deep into silicon, mask slightly misadjusted, active region is exposed.

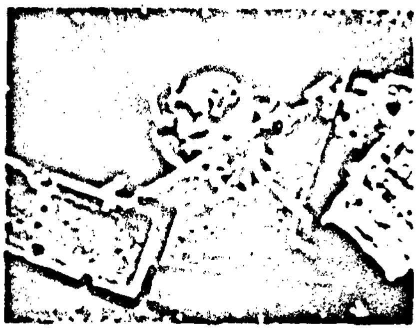

Fig.11: Part of the protecting oxide and Al-metalization etched away

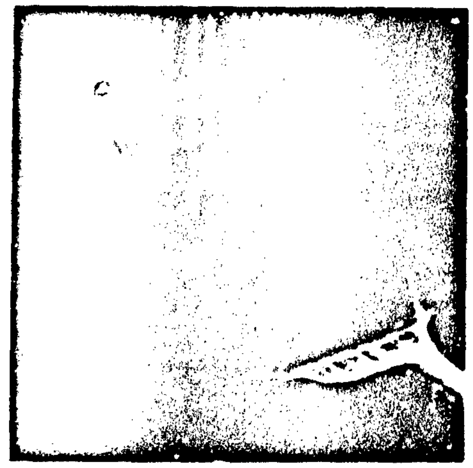

Fig.12: Good lead bond on chip

Fig.13: Rejected lead bond on chip

Fig.14: Chip Bond of Fig. 3 with signs of purple plaque as seen in the SEM

Fig.15: Remaining bond on chip of Fig. 3 shows purple plaque with cracks under the bond

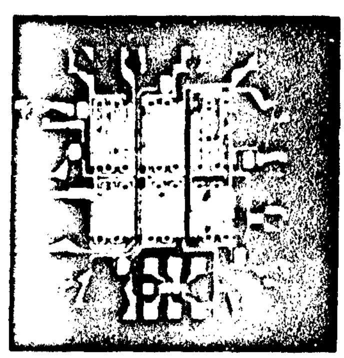

Fig.16: SOS CD4007 C-MOS circuit with MOS transistor (2 per gate) connected as protection between gate and source of inputs (50x)

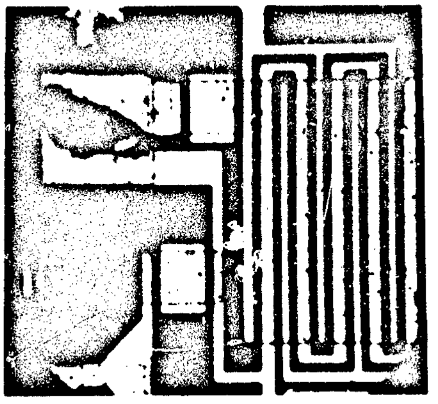

Fig.17: Protection transistors of Fig. 16 in more detail (200x)

AGARD Lecture Series No. 81

Avionics Design for Reliability

This Bibliography with abstracts has been prepared to support AGARD Lecture Series No. 81 by the Scientific and Technical Information Office of the US National Aeronautics and Space Administration, Washington, D.C., in consultation with Mr. W.T. Sumerlin, the Lecture Series Director.

It is hoped that this mate. al will be of value to scientists and engineers and in particular to those who are new in the field.

BIBLIOGRAPHY

TYPICAL CITATION AND ABSTRACT FROM *STAR*

NASA ACCESSION NUMBER · TITLE · AUTHOR · CONTRACT OR GRANT · REPORT NUMBER · AVAILABLE ON MICROFICHE · CORPORATE SOURCE · PUBLICATION DATE · AVAILABILITY SOURCE · COSATI CODE

N75-28078# Hughes Aircraft Co. Carlsbad Calif Industrial Products Div
STORAGE CAMERA-TUBE WITH NON-DESTRUCTIVE READOUT Final Report, 1 Jul. 1973 - 30 Sep. 1974
L S Yaggy Dec 1974 38 p
(Contract DAAB07-73-C-0330. DA Proj 1S7-62705-AH-94-2D)
(AD-A008447. ECOM-73-0330-F) Avail NTIS CSCL 09/1

The report describes the progress and reviews accomplishments on major tasks to develop a novel storage camera-tube The tube is capable of dual-mode operation either as a real-time television camera tube or as a storage camera-tube with non-destructive readout switchable on command Details of the device are described and test results are presented A sensitivity of 055 amperes per watt at 1 06 micrometer wavelength was achieved, representing 6 1/2% quantum efficiency Means of increasing 1 06 micrometer sensitivity are discussed GRA

TYPICAL CITATION AND ABSTRACT FROM *IAA*

AIAA ACCESSION NUMBER · TITLE · TITLE OF PERIODICAL · AUTHOR · AUTHOR'S AFFILIATION · PUBLICATION DATE

A74-46146 **Microminiature transformers.** A Kusko (Alexander Kusko, Inc , Needham Heights, Mass) and M Caplan (Bourns Pacific Magnetics Corp , Romoland, Calif) *(Institute of Electrical and Electronics Engineers, Annual International Magnetics Conference, 12th Toronto, Canada, May 14-17, 1974) IEEE Transactions on Magnetics*, vol MAG 10, Sept 1974, p 698-700

Requirements for microminiature transformers and inductors in aerospace applications are being met with a line of 1/8-in and 1/4 in cube units These transformers are used for audio carrier broad band and power supply service in telemetering amplifiers, inertial guidance systems and other applications The transformers are manufactured with laminations and bobbin-wound coils, usually under microscopes, to exacting electrical and environmental requirements Special manufacturing and test equipment has been developed because of the microminiature size Typical ratings are 25 mW for the 1/8-in cube, 200 mW for the 1/4-in cube Three typical applications are described (Author)

Section 1.
PROGRAM MANAGEMENT

N72 18017# Federal Aviation Administration Washington D C Maintenance Div
ACHIEVING GENERAL AVIATION SAFETY GOALS THROUGH AN AIRWORTHINESS SYSTEM
Sam J Curso 1971 16 p Presented at 7th Ann Maintenance Symp Oklahoma City Dec 1971
Avail NTIS

A number of safety goals to promote airworthiness systems for flight safety are presented. They encompass inspection rules for the design and manufacture of aeronautical products overhaul and repair manuals for aircraft maintenance operating procedures for use of manpower and manpower standards regulations for ground services and maintenance research G G

N73 23883 Office National d Etudes et de Recherches Aerospatiales Paris (France)
GENERAL GUIDELINE FOR THE DESIGN OF MANNED AEROSPACE VEHICLES
Jean Claude Wanner *In* AGARD Automation in Manned Aerospace Systems Mar 1973 8 p refs

The Franco British airworthiness authorities reviewed the set of technical specifications required for Concorde in order to insure the safety of the missions of this new transport aircraft. In order to guide the definition of these now regulations a theoretical method was developed for evaluating the reliability of the missions of manned aerospace vehicles. This method is based on an investigation of the way of occurrence of accidents. It has been seen that an accident is due to a set of incidents which can be classified into only three different types. The study of each type of incident the probability of occurrence which has to be reduced in order to increase the safety is very useful to help the designer of a new project to choose between possible solutions taking into account the reliability of the systems the possible human errors and the flight conditions Author

N75 30046 British Aircraft Corp (Operating) Ltd Bristol (England) Avionics Engineering Dept
EXPERIENCE WITH THE CONCORDE FLYING CONTROL SYSTEM
Neville Brenchley and Ronald Grant *In* AGARD Impact of Active Control Technol on Airplane Design Jun 1975 14 p

The Concorde Flight Control System is discussed along with its performance reliability and behavior in flight. Possible future developments are considered Author

N75 31484# Army Materiel Command Texarkana Tex Intern Training Center
A COMPARATIVE ANALYSIS OF RELIABILITY PREDICTION TECHNIQUES Final Report
Douglas Joseph McGowen Apr 1975 92 p refs
(AD A009282 USAMC ITC 02 08 75 103) Avail NTIS CSCL 14 4

The report describes various reliability prediction techniques utilized in the development of an equipment. The techniques described include prediction by similar system similar complexity function generic part count stress analysis and degradation techniques. These are described and compared with respect to the characteristics basic assumptions typical applications and relative accuracy GRA

A69-31136
DERIVATION OF RELIABILITY SPECIFICATIONS FOR AVIONICS SYSTEMS
W H Sellers M Berssenbrugge and A H Schwartz American Society for Quality Control Inc p 581 592 1969 *In* American Society for Quality Control Annual Technical conference 23rd Los Angeles Calif May 5 7 1969 TRANSACTIONS

Application of the Markov chain method to avionics weapons system reliability specifications. This system starts with the Mission profile which is a quantitative description of functions that the equipment must perform and the period of time over which these functions are expected to perform successfully. Failure rates are collected for the components of the system and these are formulated into a Markov chain equation which establishes the probabilities of mission success. The successful application of this technique has been demonstrated in existing avionics systems such as the B 58 and the F 106 B H

A72 32461 # **The influence of avionic equipment of aircraft timekeeping.** R W Howard (GEC Marconi Electronics, Ltd Chelmsford Essex, England) In Managing to be on time A total system approach in aircraft operations Royal Aeronautical Society, Spring Convention, London, England, May 10, 11, 1972 Proceedings London, Royal Aeronautical Society, 1972 19 p

Search for possible improvements in airline timekeeping which could result from the avionics aspects by dividing the study into two major parts in flight operations and aircraft unserviceability. Avionics will affect mainly the categories of weather (10%) technical and engineering (15%) and air traffic (5%). Other causes account for the remaining 70%. An all weather landing capability should remove most of the weather delays and the additional equipment involved should not increase the level of delays in the technical and engineering categories if the operation of the all weather system is not 'dispatch critical.' It appears that total improvement in delays of up to 15% might be the aim for aircraft in current service if it is accepted that the proposed electronic additions are not 'dispatch critical.' In the future, fly by wire CCV (Control Configured Vehicle) requirements and scheduled all weather landing will demand a change in emphasis and such elements will become 'dispatch critical.' F R L

A73-27158 **On the improvement in survivability for avionics equipment.** K A Pullen Jr (U S Army Ballistics Research Laboratories Aberdeen Proving Ground Md) In Asilomar Conference on Circuits and Systems 6th Pacific Grove Calif November 15 17 1972 Conference Record North Hollywood Calif Western Periodicals Co 1973 p 154 161 6 refs

Because of the nature of electronic units the impact of a projectile or fragments on it will usually either produce an immediate (less than one second) K kill for the unit or it will survive. As a practical matter improvement of survivability is conveniently achieved by use of parallel processing paths thereby making the target many times more vulnerable. Attention is given to the series redundancy problem and ground loop control. It is shown that some relatively simple changes may lead to substantial improvements of survivability in electronic equipment for use on aircraft and also that with properly designed protective equipment the arrangements for providing the redundancy need not introduce significant failure problems of their own F R L

A73-27384 # **Improvements in the use of FAA resources for system performance assurance** D F Babcock (Stanford Research Institute, Menlo Park, Calif) In Radio Technical Commission for Aeronautics, Annual Assembly Meeting, Washington, D C November 9 10, 1972 Proceedings Washington D C Radio Technical Commission for Aeronautics 1972 12 p

Methods are needed for assessing system performance and for estimating system costs. What is sought is a means for giving adequate visibility to the salient features of the system that require attention either from a performance or cost viewpoint. In general it is feasible to prepare a definition and description of the National Airspace System (NAS) and to create performance measures and set goals for NAS performance. It is recommended that life cycle models for all major system elements should be established and maintained that system criticality be analyzed and that a plan should be formulated to allocate resources F R L

A73-33605 **The role of testing in achieving aerospace systems effectiveness.** A M Smith (General Electric Co, Philadelphia, Pa) and T D Matteson (United Air Lines, Inc, San Francisco, Calif) In Annual Reliability and Maintainability Symposium Philadelphia, Pa, January 23 25, 1973 Proceedings New York, Institute of Electrical and Electronics

Engineers, Inc., 1973, p. 36-41

The findings of a study of the relationship between testing and the achievement of effectiveness in aerospace systems are summarized. The study was conducted by the AIAA Systems Effectiveness and Safety Technical Committee and covered various aspects of test program requirements, philosophy and experience with spacecraft, launch vehicles, DOD aircraft, and commercial aircraft. The conclusion is that acceptance tests play a less-than dominant role in the achievement of systems effectiveness. V Z

A74-14142 **Reliability in avionics.** P. H. Mead (Ferranti, Ltd., Edinburgh, Scotland) *Flight International*, vol. 104, Nov. 29, 1973, p. 900, 901

In avionics, advanced technology has brought greater complexity with wider use being made and increased reliance being imposed on more and more components. Complexity, however, may increase unreliability to wholly unacceptable levels threatening safety, confidence, and economy. Built-in test equipment can make a significant economic contribution by allowing correct diagnosis on the flight line and making it unnecessary to remove serviceable units. The benefits and challenges of new technology and cost effective reliability are considered. As would be expected, problems in reliability are in proportion to the degree of sophistication or technological advance in avionics equipment. F R L.

A74-18597 **Theory and practice of avionics reliability (Theorie et pratique de la fiabilite des equipements).** M. M. Ravier (Compagnie Nationale Air France, Paris, France) *L'Aeronautique et l'Astronautique*, no. 42, 1973, p. 18-24. In French.

Some of the theoretical and practical aspects of the maintenance and reliability of avionics systems are reviewed. Discussed topics include the actuarial approach to failure expectancy as a function of age, acceptable reliability criteria, service life extension and reliability, maintenance routines, and manufacturer airline liaison. M V E

A74-38583 **Avionic equipment reliability and low life cycle cost.** W. R. Perrigo (USAF, Avionics Laboratory, Wright-Patterson AFB, Ohio) and J. L. Easterday (Battelle Memorial Institute, Columbus, Ohio). In: NAECON '74; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 13-15, 1974. New York, Institute of Electrical and Electronics Engineers, Inc., 1974, p. 521-532. 12 refs.

Basic activities in the conduct of a reliability program are related to technical program aspects, management visibility and control, and philosophical concepts of a reliability program. Questions of initial or preprogram planning are examined. The program manager must make certain that a realistic, achievable goal is defined for the reliability program. A program manager's checklist is presented. Major management functions are summarized, taking into account the evaluation of the actual status of each activity in relation to the schedules, reliability task status reports, and reliability monitoring. G R

Systems Research Labs., Inc., Dayton, Ohio
DIGITAL AVIONICS INFORMATION SYSTEM DESIGN OPTION DECISION TREES Interim Report, 3 Dec. 1973 - 15 Apr. 1975
Kenneth D. Potter and Duncan L. Dieterly. Jun. 1975. 51 p
(Contract F33615-74-C-4019)
(AD-A014333/9GA; AFHRL-TR-75-29(2)) HC $3.75/MF $2.25

The DODTs for a DAIS system were developed to determine the decision points in a design process which may be of importance in projecting the input of new technology on human resource parameters. The DODTs for the DAIS system were refined through the process of extensive reevaluation by experts in the field both in industry and the Air Force. They were then used in another phase of the study to actually determine the design choice impact on selected human resource parameters. The DODT technique allows for a rather extensive evaluation of the design choices for the completion of a total system. In addition to the major purpose of the DODTs for this research project, as a tool for assisting in quantifying human resource requirements of various technologies, they may be used for a series of other management actions. GRA

Joint Technical Coordinating Group on Electronics Equipment Reliability
FINAL REPORT OF THE JOINT LOGISTICS COMMANDERS ELECTRONIC SYSTEMS RELIABILITY WORKSHOP
1 Oct. 1975. 334 p
AD-A016 826/ OGA
HC $9.50/MF $2.25

The Workshop represents a culmination of almost ti e years of effort by the Joint Technical Coordinating Group on Electronic Equipment Reliability (JTCG EER) which was devoted to a series of investigations for improving reliability and procurement practices related to microcircuits. After making substantial progress on its device related projects, the JTCG EER decided to organize the Electronic Systems Reliability Workshop in order to address the system reliability problem and to consider means of developing improved management procedures, documentation standards and analytic and testing techniques for producing more reliable systems. The Workshop was organized into seven work groups, namely: Acquisition, Reliability Management, Operational Reliability Management, Reliability Testing, Reliability Documentation, Reliability Analysis, Reliability Design Techniques, and Software Reliability. GRA

Section 2.
DESIGN FOR HIGH RELIABILITY

N73-28249# Rockwell International Corp., Anaheim, Calif. Electronics Group
SURVIVABLE P-CHANNEL METAL-OXIDE-SEMICONDUCTOR (PMOS) COMPUTER DESIGN Final Report, 20 Mar. - 20 Sep. 1972
Daryl T. Butcher, Howard Maddox, and Robert L. Nielsen Mar. 1973 135 p refs
(Contract F33615-72-C-1732; AF Proj. 3176)
(AD-759189; C72-446/501; AFAL-TR-73-31) Avail: NTIS CSCL 09/2

The significance of this project to the Air Force is the fact that it provides assessment and develops specifications for employment of advanced radiation-hardened field effect Metal-Oxide-Semiconductor (MOS) and Metal-Nitride-Oxide-Semiconductor (MNOS) technologies for military space computer systems. The characteristics and capabilities of the device and packaging technologies required for MOS/MNOS computer construction are defined and compared to the techniques and hardware requirements for long-life computer systems. A computer architecture is derived from the comparison analysis. (Author Modified Abstract) GRA

N73-22988# Ballistic Research Labs., Aberdeen Proving Ground, Md.
EFFECTS OF REDUNDANCY ON SURVIVAL OF CRITICAL AVIONICS EQUIPMENT
Keats A. Pullen Jan. 1973 36 p refs
(DA Proj. 1T6-62708-A-068)
(AD-757152; BRL-MR-2266) Avail: NTIS CSCL 09/5

The design of simple circuits capable of keeping communications equipment in operation under conditions of failure of vital sections or sub-units of a system are described. Analyses are included which indicate possible routes for improvement of equipment survivability in a battlefield-type environment. Author (GRA)

N75-28078# Hughes Aircraft Co., Culver City, Calif. Display Systems and Human Factors Dept.
BREADBOARD HIGHLY RELIABLE VERTICAL TV DISPLAY SYSTEM, PHASE 2 Final Report, 15 Mar. - 15 Dec. 1974
G. Wolfson and B. W. Keller Feb. 1975 96 p
(Contract N62269-74-C-0342)
(AD-A008241; HAC-P75-44R; HAC-Ref-D2143) Avail: NTIS CSCL 09/5

The tasks performed were two-fold. First, a state-of-the-art CRT was evaluated in an effort to validate the CRT life model, developed during Phase II and to relate CRT performance to reliability. The second task was the development and fabrication of key elements of the programmable symbol generation with the objective of providing improved performance and reliability. These key elements included the field refresh memory, memory input format logic, memory output format logic, post processor and master timing and control. The effort expended in the development of these key elements has resulted in significant achievements which should lead to both increased symbol generator performance and reliability. GRA

A71-18833 **Operating system reliability for the Navy advanced avionic digital computer.** Ronald S. Entner (U.S. Naval Air Systems Command, Washington, D.C.) and Edward H. Bersoff (Logicon, Inc., Falls Church, Va.). *IEEE Transactions on Aerospace and Electronic Systems*, vol. AES-7, Jan. 1971, p. 67-72. 5 refs.

This paper discusses reliability aspects of a modular multiprocessor currently under development by the Naval Air Systems Command. The operating system, or executive of this computer may be implemented in various ways. These include a totally software 'floating executive,' one dedicated to a specific processor, or an executive consisting of special-purpose hardware. The objections to hardware executives, especially for avionic applications, include a supposed degradation in system reliability. This paper shows that under certain conditions this degradation need not occur. (Author)

A72-16574 **A Bayesian analysis of avionic subsystem built-in test.** E. C. Harmon (General Dynamics Corp., Fort Worth, Tex.). *IEEE Transactions on Aerospace and Electronic Systems*, vol. AES-7, Sept. 1971, p. 982-987.

A major development in test philosophy of aircraft being built today and those being designed for the immediate future is the incorporation of on-board, computer-controlled 'built-in' testing (BIT) into the airplane as part of the avionic subsystem. A requirement being imposed by today's specifications is a probability of 0.95 or better that the BIT function will detect a failure. It is shown that a single specification of BIT capability is insufficient to completely define the requirements for BIT. The proof of this conclusion is offered in the form of an analysis of the conditional probabilities involved in the occurrence and reporting of subsystem failures. (Author)

A72-35581 **Modular avionic computer.** E. C. Gangl (USAF, Aeronautical Systems Div., Wright-Patterson AFB, Ohio). In: NAECON '72; Proceedings of the National Aerospace Electronics Conference, Dayton, Ohio, May 15-17, 1972.
New York, Institute of Electrical and Electronics Engineers, Inc., 1972, p. 248-251. 11 refs.

This paper proposes a modular avionic computer concept that can be easily standardized. Since the advent of large avionic systems the Air Force has been plagued with a multitude of diverse processors throughout the aircraft. These computers are always dissimilar and create a tremendous support and inventory problem. This paper suggests a modular computer concept that could be used wherever sequential processing is required in the aircraft. Its design permits many different applications by tailoring it to the task through microprogramming. (Author)

A72-37032 # **Integrity of flight control system design.** I. S. Ment (Smiths Industries, Ltd., Wembley, Middx., England). *Aircraft Engineering*, vol. 44, July 1972, p. 4, 5.

Determination, for airborne systems, of the effect of failures on the airworthiness of an aircraft. The limit on acceptable unreliability shows that economics are not permitted to dictate where safety is concerned. In general, things fail because they are overstressed. Electronic components, and hence systems, follow this rule. Various methods of improving reliability are outlined. If it is required to show in advance of in-service experience that certain failures of a system have a very low probability, there is no practical alternative to that of designing a system with redundancy so that the failure rate of its constituent parts can be established in a reasonable time and computation of the effect of redundancy carried out. F.R.L.

A73-17572 # **DAIS - A major crossroad in the development of avionic systems.** B. List (USAF, Avionics Laboratory, Wright-Patterson AFB, Ohio). *Astronautics and Aeronautics*, vol. 11, Jan. 1973, p. 55-61.

The Digital Avionics Information System (DAIS) is discussed as a new approach to meet the requirements of modern military supersonic all weather precision weapon delivery systems operable by small crews. The approach described provides ability to modify an avionic system by means of software rather than hardware changes, and to use modular or common equipment design in different types of aircraft. Further it gives a significantly greater total system mean time between failures (MTFB) through the planned use of redundancy at subsystem, equipment, and component levels, and a greater flexibility of adding new sensors and capabilities to the system without rewiring the aircraft. V.P.

A73-32440 **Onboard electronic equipment optimization and redundancy (Optimisation des équipements électroniques de bord et redondance).** J. de Corlieu (Thomson-CSF, Bagneux, Hauts-de-Seine, France). In: Electronics and civil aviation; International Conference, Paris, France, June 26-30, 1972, Reports. Volume 1. Paris, Editions Chiron, 1972, p. 377-384. In French.

The optimization of redundancy in application to onboard electronic equipment for civil and military aircraft is discussed. In particular, the hypotheses underlying the concept of reliability are reviewed, along with future trends in the philosophy and practices of reliability and redundancy. M.V.E.

A74-13808 **Cost effective built-in test for advanced aircraft electrical systems.** H. Brown (U.S. Naval Material Command, Naval Air Development Center, Warminster, Pa.) and H. W. Heinzman (LTV Aerospace Corp., Vought Systems Div., Dallas, Tex.). In: Automatic support systems for advanced maintainability; International Symposium, Arlington, Tex., November 5-7, 1973, Record. New York, Institute of Electrical and Electronics Engineers, Inc., 1973, p. 53-60. 7 refs.

This paper presents a method for utilizing the data handling portion of the SOSTEL multiplex system to provide a cost effective built-in test (BIT) capability to isolate faults to the line replaceable unit (LRU). The evolved techniques provide a means for determining the health of each of the 2048 input and 2048 output controls which are multiplexed by the system. In addition four techniques to automatically test the data handling circuits are also discussed. The BIT system as defined is efficient, small in size and weight, and cost effective because most of the data circuits are time shared to accommodate BIT data. The BIT data is used inflight in the solution of power management equations to permit programming of redundancy and safety interlocks. Two types of maintenance displays are discussed, a maintenance panel and an onboard strip printer. The BIT system is compatible with air-to-ground data link to maintenance data. (Author)

A74-39929 **Large scale integration application for satellite on-board processing.** R. K. Geiger (U.S. Navy, Electronic Systems Command, Washington, D.C.). *(Armed Forces Communications and Electronics Association, Annual Convention, 28th, Washington, D.C., June 11-13, 1974.) Signal*, vol. 28, Aug. 1974, p. 42-44.

More efficient satellite relays can reduce the requirements concerning the large number of terrestrial elements in the Navy's communication networks. LSI technology could improve communications spacecraft performance with the aid of on-board processing. On-board processing includes any function which may alter, direct, control, store, or inhibit the signals relayed by the spacecraft. One of the most significant features of LSI technology is high reliability. The FLTSATCOM fleet broadcast equipment is the first LSI implementation of on-board processing. G.R.

A75-23467 **Impact of avionic design characteristics on technical training requirements and job performance.** K. W. Potempa, R. S. Luckew (USAF, Human Resources Laboratory, Wright-Patterson AFB, Ohio), and L. M. Lintz (McDonnell Douglas Astronautics Co., St. Louis, Mo.). *Human Factors*, vol. 17, Feb. 1975, p. 13-24. 9 refs. Contract No. F33615-71-C-1620.

This study was performed in two phases. The first phase concentrated on the influence of avionic design and technical training factors on student performance. The second phase dealt with the impact of design and personnel factors on the performance of technicians in operational Air Force units. Avionic components were scaled on a variety of design characteristics, and data were collected on the task time and error performance of students and technicians performing a functional checkout maintenance task on the components. Personnel data were also obtained on each subject. Multiple-regression equations were then developed to predict task performance from design characteristics and personnel measures. The multiple R's for students were 0.57 for time and 0.82 for errors. The multiple R's for technicians ranged from 0.60 to 0.88, depending on the type of maintenance and criterion measure used; all R's were significant at the level of p less than 0.001. (Author)

A75-26720 * **Digital avionics-overview - Airframe manufacturer's viewpoint.** R. Dunn (Boeing Commercial Airplane Co., Seattle, Wash.). *American Institute of Aeronautics and Astronautics, Digital Avionics System Conference, Boston, Mass., Apr. 2-4, 1975, Paper 75-552.* 6 p.

The system requirements in new aircraft are related to changes regarding the criteria used to rate the worth of an aircraft. Aspects of aircraft economics, noise, and ecological considerations have become very important. Better performance at lower costs can be provided by a utilization of advanced digital technology in place of the analog systems employed in present aircraft. Research and development programs conducted in the area of digital technology by an American aerospace corporation are discussed. G.R.

A75-26725 * **Flight-critical digital control system evaluation.** L. E. Fairbanks (General Electric Co., Binghamton, N.Y.) and J. E. Templeman (Boeing Commercial Airplane Co., Seattle, Wash.). *American Institute of Aeronautics and Astronautics, Digital Avionics System Conference, Boston, Mass., Apr. 2-4, 1975, Paper 75-566.* 15 p. 6 refs. Research sponsored by the U.S. Department of Transportation.

The flight controls development study task was developed to permit technology investigations into selected areas of triple-channel, fail-operational, analog and digital system designs. An application model based on a flight-critical control system is considered. A system description is given, taking into account the laboratory configuration and analog subsystem, the incremental control processor subsystem, and the whole word computer subsystem. Performance comparisons are discussed along with aspects of software development and control. Attention is also given to the preflight test/failure mode and effects studies. G.R.

A75-31129 **An advanced fault isolation system for digital logic.** N. Benowitz, D. F. Calhoun, G. E. Alderson (Hughes Aircraft Co., Data Systems Div., Culver City, Calif.), J. E. Bauer (U.S. Navy, Naval Air Engineering Center, Lakehurst, N.J.), and C. T. Joeckel (U.S. Naval Material Command, Naval Air Development Center, Warminster, Pa.). *IEEE Transactions on Computers*, vol. C-24, May 1975, p. 489-497. 8 refs. Contract No. N62269-73-C-0132.

Built-in test (BIT) techniques for cost-effective fault detection and fault isolation to a digital subsystem and to the faulty module there in are described. The OR of resulting module pass-fail signals indicates subsystem faults, where as identification of a module fail signal provides isolation to a faulty module. Coding techniques are discussed, with tradeoff of speed, test effectiveness, and logic requirements for each. It is shown that less power and fewer units are necessary for the same level of performance and reliability, since only one rather than three units must operate to eliminate failure. S.D.

Ultrasystems, Inc., Newport Beach, Calif.
FAULT TOLERANT AVIONICS SYSTEMS ARCHITECTURES STUDY Final Report
Lee R. Murphy, Algirdas A. Avizienis, David A. Rennels, Lyle D. McNeely and Roger L. Fulton Jun. 1974 490 p
(Contract F33615-73-C-1163; AF PROJ.)
(AD-784879; 74/8-20-24; AFAL-TR-74-102) Avail: NTIS

The report presents the results of a study to apply fault tolerance techniques to avionics systems architectures. This study included the following tasks: (1) definition of a general avionics baseline system consisting of integrated pilot controls and displays, strapdown inertial reference unit, fly-by-wire automatic flight control subsystem, multiplex data bus and distributed computation network; (2) development of a fault-tolerant avionics distributed computation subsystem; (3) development of optimum avionics system partitioning, redundancy implementation and redundancy management techniques; (4) development of subsystem fault detection, isolation, and recovery techniques; and (5) analysis and determination of the costs versus benefits of fault tolerant avionics system design. (Author)

Air Force Avionics Lab., Wright-Patterson AFB, Ohio.
AN INTRODUCTION TO FAULT-TOLERANT DESIGN TECHNIQUES Technical Report
Thomas E. Tyson Jun. 1975 36 p Supplement to report dated Jun. 74, AD-784879
(Project AF-2003)
(AD-A013934; AFAL-TR-74-334)

This report introduces the concept of fault-tolerant architectures and surveys general techniques for the design of fault tolerant systems. The techniques discussed are for digital systems or systems that can be visualized as being digital in nature. (Author)

Messerschmitt-Boelkow-Blohm, Muenchen, Germany.
INTEGRATION OF THE COMBAT AVIONICS [INTEGRATION DER AVIONIK VON KAMPFFLUGZEUGEN]
Walter H. Vogl 5 Jun. 1974 4 p In GERMAN
(74-060049)

Using the example of avionics, the concept of a system testing is explained which permits investigation and integration of complex airframe airborne weapon systems already during the development phase under a broad range of realistic combat conditions. The purpose of this is to install an already fully functioning weapon system into the airframe. An optimization method is described which has been worked out for this form of system development. It is particularly suited for high-performance combat aircraft. (Author)

Section 3.
SELECTION OF COMPONENTS AND PARTS

N72-18067# Army Electronics Command Fort Monmouth N J
Electronics Technology and Devices Lab
ENGINEERING EVALUATION OF AIRCRAFT BATTERIES
Sylvia Duze Jul 1971 36 p refs
(DA Proj 1T6 62705 A 053)
(AD 733289 ECOM 3456) Avail NTIS CSCL 10 3

Changes in aircraft technology and advances in electronic and electrical equipment design have caused increased demands for electric power Batteries in the smallest and lightest design must be capable of delivering high rate currents under all ambients for starting power have good high rate charge acceptance and be available in the fully charged state in case of emergency The report details all the problem areas evaluates the various secondary electrochemical systems in terms of aircraft use describes the redesign efforts of the Military Services and presents a critique of specifications covering aircraft batteries Author (GRA)

N72-32248# Bendix Corp Sidney N Y Electrical Components Div
RELIABLE INTEGRATED WIRE TERMINATION DEVICES Semiannual Report, 1 Jul - 31 Dec 1971
D L Pfendler and D H Gould Jun 1972 93 p refs
(Contract DAAB07-71-C-0090 DA Proj 1F1 62203-A-119)
(AD-744478 ECOM-0090-2) Avail NTIS CSCL 09/1

The purpose of the investigation is to cover the design and evaluation of a wire termination system capable of interconnection to a variety of multi contact connectors such as cylindrical rectangular rack and panel printed circuit board and terminal junction devices The connective devices are to be capable of assembly and maintenance with a common tool for terminal insertion and withdrawal In addition the various connective devices shall be capable of reliably withstanding the environmental conditions encountered by both ground and airborne Army equipment Primary emphasis is directed toward a significant improvement of the reliability and maintainability of wiring systems in Army aircraft Protype test samples containing size 22D terminals have been fabricated and tested Prototype test samples containing size 20 terminals (both metallic and dielectric retention) are being fabricated and will be evaluated according to the prepared test procedure Terminal insertion and removal tools have been revised and will be evaluated according to a test procedure to be prepared Author (GRA)

N73-22144# Sperry Rand Corp St Paul Minn Defense Systems Div
MEDIUM SPEED MASS RANDOM ACCESS MEMORY MODULE Final Report
Robert A White and Glenn M Krueger Griffiss AFB N Y RADC Jan 1973 34 p
(Contract F30602 69 C 0325)
(AD 755937 PX 5407 50 RADC TR 72 331) Avail NTIS CSCL 09/2

The objective of the program is to develop a preproduction model of a solid state plated wire memory module to operate in an airborne or tactical field environment with a command and control system computer This module was designed within the basic constraints that the completed 10 million bit module is both random access in its retrieval mode and reliable in a tactical field application while the cost per bit of the module in production remained sufficiently low ($0 01 to $0 015 per bit) to be acceptable to the users The module was designed fabricated and tested to the requirements of MIL E 5400 over an operating range of 0C to 55C Basically the final environmental test results bore out the design criteria in that the module was successfully tested for shock vibration humidity etc without any evidence of significant design problems The module is presently at Rome Air Development Center where it is scheduled for use in various Air Force applications Author (GRA)

A72-34683 **Hybrid LSI logic modules for aerospace** J A Cicrio S M Stuhlbarg and R E Thun (Raytheon Co Bedford Mass) In Electronic Components Conference 22nd Washington D C, May 15-17, 1972 Proceedings New York Institute of Electrical and Electronics Engineers Inc 1972 p 185-200

A set of hybrid LSI logic modules has been developed which provides architectural building blocks for a wide range of aerospace and military digital systems An order of magnitude increase in density and reliability has been achieved over conventional integrated circuit packaging techniques by the combined use of passivated, beam leaded TTL arrays and ceramic based high density interconnection networks This concept becomes technically and economically feasible through the use of extensive automation in layout design mask making, and test generation The paper describes the various technologies employed, the design automation techniques developed and the logic functions implemented (Author)

A72-34686 * **Techniques for control of long-term reliability of complex integrated circuits I Reliability assurance by test vehicle qualification** N W Van Vonno (Harris Semiconductor, Melbourne Fla) In Electronic Components Conference 22nd, Washington, D C, May 15-17, 1972, Proceedings New York, Institute of Electrical and Electronics Engineers, Inc, 1972 p 463-466 5 refs NASA supported research

Development of an alternate approach to the conventional methods of reliability assurance for large scale integrated circuits The product treated is a large scale T squared L array designed for space applications The concept used is that of qualification of product by evaluation of the basic processing used in fabricating the product, providing an insight into its potential reliability Test vehicles are described which enable evaluation of device characteristics, surface condition, and various parameters of the two level metallization system used Evaluation of these test vehicles is performed on a lot qualification basis, with the lot consisting of one wafer Assembled test vehicles are evaluated by high temperature stress at 300 C for short time durations Stressing at these temperatures provides a rapid method of evaluation and permits a go/no go decision to be made on the wafer lot in a timely fashion (Author)

A73-32486 **Analysis of the reliability of airborne material in an airline company - Objectives and methods (L'analyse de la fiabilité du matériel volant dans une compagnie aérienne - Objectifs et méthodes).** J. L. Lesage (Secrétariat Général à l'Aviation Civile, Paris, France) In Electronics and civil aviation, International Conference, Paris, France, June 26-30, 1972, Reports Volume 2 Paris, Editions Chiron, 1972 p 877-880 In French

All major airlines carry out a permanent follow-up of the reliability of their airborne material Overall, the methods utilized at Air France are not unique, and can be found in other European and American countries. This is due to the very good relations which exist between the technical services of different companies which favor the exchange of information or new methods Reliability is defined as a method of maintaining safety at an acceptable level, and a method of reducing costs In the course of the last ten years the balance sheet of reliability studies at Air France has been largely positive F R L

A73-34731 **Failure analysis used to vindicate JANTX components** R . People (Westinghouse Defense and Electronic Systems Center Baltimore Md) In Electronic Components Conference 23rd Washington D C May 14-16 1973 Proceedings New York Institute of Electrical and Electronics Engineers Inc 1973 p 349-354

With increased emphasis on reliability in government contracted systems more stringent requirements have been placed on semiconductor components resulting in the MIL S 19500 JANTX MIL S 38510 and MIL STD 883 specifications These specifications add processing and power conditioning to 100% of the components in a lot submitted for acceptance as a JANTX type prior to inspection tests to verify Lot Tolerance Percent Defective (LTPD) The post mortem examination of JANTX component rejection occurring during the various stages of test in the manufacturing of an airborne electronics system has shown that the failures were mainly associated with circuit design manufacturing and test problems and these were resolved through appropriate corrective action Analysis of these failures played a central role in determining the most effective

corrective action and in verifying that the corrective action had achieved the desired result F R L

A74 20969 **DC 10 avionics parts reliability in review** R S Baten (Douglas Aircraft Co Long Beach Calif) In Annual Reliability and Maintainability Symposium Los Angeles Calif January 29 31 1974 Proceedings New York Institute of Electrical and Electronics Engineers Inc 1974 p 403 408

The McDonnell Douglas DC 10 aircraft program has demonstrated the effectiveness of a number of reliability and quality engineering controls and disciplines Notable among them are several key controls on electrical electronic and electromagnetic parts in the avionics systems A qualitative review of those parts controls is presented utilizing DC 10 case histories (actual part failure problems) as a basis for discussion and evaluation of the relative effectiveness of the controls The controls that have shown most room for improvement (judged by the impact of their deficiencies on fielded equipment reliability) are (1) part failure reporting analysis and corrective action (2) multiple source part procurement and (3) the designation and control of manufactured part quality Author

A74 38519 **One chip stored program magnetic bubble processor** R A Naden and J C Linn (Texas Instruments Central Research Laboratories Dallas Tex) In NAECON 74 Proceedings of the National Aerospace and Electronics Conference Dayton Ohio May 13 15 1974 New York Institute of Electrical and Electronics Engineers Inc 1974 p 42 49 Contract No F33615 73 C 1029

A one chip magnetic bubble stored program processor designed for operation in severe military environments is described Expected application is in the area of dedicated control Advantages are expected over a computing power equivalent semiconductor processor in the areas of radiation hardness weight volume power dissipation and reliability The price paid for these advantages is a low speed of approximately 1000 instructions per second However it is believed that systems comprising the single bubble chip magnetic package and minimal support electronics will be small and cheap enough to spread throughout avionics systems for distributing the computing load (Author)

A74-45145 **Microminiature transformers** A Kusko (Alexander Kusko Inc Needham Heights Mass) and M Caplan (Bourns Pacific Magnetics Corp Romoland Calif) *(Institute of Electrical and Electronics Engineers Annual International Magnetics Conference 12th Toronto Canada May 14 17 1974) IEEE Transactions on Magnetics* vol MAG 10 Sept 1974 p 698 700

Requirements for microminiature transformers and inductors in aerospace applications are being met with a line of 1 8 in and 1 4 in cube units These transformers are used for audio carrier broad band and power supply service in telemetering amplifiers inertial guidance systems and other applications The transformers are manufactured with laminations and bobbin wound coils usually under microscopes to exacting electrical and environmental requirements Special manufacturing and test equipment has been developed because of the microminiature size Typical ratings are 25 mW for the 1 8 in cube 200 mW for the 1 4 in cube Three typical applications are described (Author)

Royal Aircraft Establishment Farnborough England
OUTPUT FILTERS FOR AIRCRAFT TYPE CYCLOCONVERTORS Technical Report
N J Carter Apr 1971 44 p
(AD 740833 RAE TR 71088)

In the report the performance of low pass power filters suitable for the prime electrical power supply in aircraft is analyzed and discussed Three types of filter are considered and a computer program is used to determine the response of the filters when loads of various power factors are applied The analysis concludes that the L section filter represents the optimum arrangement for cycloconvertor applications (Author)

US NAVY Aviation Supply Office Philadelphia Pa
BURN IN CONSIDERATION IN THE PROCUREMENT OF AIRBORNE AVIONICS REPAIR PARTS
A A Giordano Def Prep Association Washington D C 1974 14 p Logistics An emerging technology meeting report Fort Lee Va Feb 26 27 1974 p 11 24
(75 042878)

The role of burn in of repair parts and the relation to reliability of operational equipment is considered Problems of variation of this role with the level of repair part (i e part assembly black box) for maximum support of operational equipment of manufacturer's responsibility of justification of the high costs of burn in as cost effective on a logistics support basis of whether burn in of repair parts really increases fleet support are examined Costs of burn in are scrutinized to highlight fleet support impacts Principles developed in aviation supply office to guide establishment of specific burn in requirements are presented It is concluded that burn in of repair parts cannot be taken for granted its economic impact is too great Recommendations are made to expand on the principles to expose the problems and to provide better input information during the provisioning process (Author)

Section 4.
ENVIRONMENT CONSIDERATION

A74 38552 **Advanced environmental control system** W. C. Savage (USAF, Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio). In: NAECON '74; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 13-15, 1974. New York, Institute of Electrical and Electronics Engineers, Inc., 1974, p. 308-310.

The described environmental control system is being developed to provide high environmental reliability of aircraft subsystems. Delivery of a steady supply of clean, cool, dry air under all mission conditions is ensured by using an improved heat exchanger separator combination to remove effectively large amounts of moisture and to eliminate wasteful reheat. The design of the high pressure condensing automatically rotating heat exchanger is described. V.P.

A74 38741 # **Aircraft avionics environmental control analysis procedures for optimized life cycle cost.** B. T. Pizak (U.S. Naval Material Command, Naval Air Development Center, Warminster, Pa.), S. A. Campbell, and K. J. Taylor (General Dynamics Corp., Convair Aerospace Div., San Diego, Calif.). In: National Conference on Environmental Effects on Aircraft and Propulsion Systems, 11th, Trenton, N.J., May 21-23, 1974, Proceedings. Trenton, N.J., U.S. Naval Air Propulsion Test Center, 1974. 18 p. 9 refs. Navy-supported research.

The cost analysis procedures considered are concerned with the life cycle cost advantages of the various environmental control systems. These procedures can, therefore, be used to optimize the environmental control systems around life cycle cost. Examples of a use of the procedures for a fighter and an ASW aircraft are discussed. It is found that in both cases considerable cost savings can be realized by utilizing constant temperature avionics. G.R.

A74 38569 **The application of environmental simulation and testing to reconnaissance needs.** J. C. Haley (USAF, Avionics Laboratory, Wright-Patterson AFB, Ohio). In: NAECON '74; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 13-15, 1974. New York, Institute of Electrical and Electronics Engineers, Inc., 1974, p. 421-423.

A75 10802 **Improved vibration design and test procedure for aircraft.** C. J. Beck, Jr. (Boeing Aerospace Co., Seattle, Wash.). *Society of Automotive Engineers, National Aerospace Engineering and Manufacturing Meeting, San Diego, Calif., Oct. 1-3, 1974, Paper 740815.* 6 p. Members, $1.75; nonmembers, $2.75.

Recent experience with vibration qualification of avionics for the B-1 airplane has revealed deficiencies in commonly used vibration design and test procedures. Specific examples of deficiencies are discussed. Recommendations for improving vibration design and test procedures are presented in the areas of environmental prediction, qualification testing, and use of vibration isolators. Suggestions are made relative to vibration design and testing in light of the 'try before buy' concept. (Author)

A75-40858 # **Compact heat exchangers for the Space Shuttle.** R. B. Trusch and J. Nason (United Aircraft Corp., Hamilton Standard Div., Windsor Locks, Conn.). *ASME, SAE, AIAA, ASMA, and AIChE, Intersociety Conference on Environmental Systems, San Francisco, Calif., July 21-24, 1975, ASME Paper 75-ENAs-54.* 14 p. Members, $1.00; nonmembers, $3.00.

Lightweight, high density plate fin heat exchangers will be used in the Space Shuttle Atmosphere Revitalization Subsystem (ARS) and in the Freon Coolant Loop (FCL). An advance in the state of the art of compact heat exchanger design has been effected with the use of fin heights of 0.020 and 0.002 in. fin thicknesses. The advance provided a significant weight savings to be made on nine types of ARS and FCL heat exchangers. The GSE heat exchanger, for example, provides cooling in a core designed to transfer heat at the rate of 0.43 kw/cu in. of core, including a redundant cooling pass. The air to water, water to Freon 21, Freon 21 to Freon 21, Freon 21 to FC-40, Freon 21 to Hydraulic fluid heat exchanger configurations are described. A summary of analytical design techniques, trade-off studies, and test results are presented as well as the approaches selected for handling up to five heat transport fluids in a single core unit. (Author)

A75-40882 # **Cost-effectiveness of refrigerated air for avionics cooling on wide-body commercial aircraft.** W. S. Boronow (Douglas Aircraft Co., Long Beach, Calif.). *ASME, SAE, AIAA, ASMA, and AIChE, Intersociety Conference on Environmental Systems, San Francisco, Calif., July 21-24, 1975, ASME Paper 75-ENAs-9.* 10 p. Members, $1.00; nonmembers, $3.00.

The costs associated with initial procurement, maintenance, and spares provisioning of avionics equipment for current commercial aircraft accentuates the need to keep the cost of ownership to a minimum. This paper discusses the tradeoffs involved in adding a refrigeration system for avionics cooling to improve avionics reliability. The results of an analysis are presented parametrically for a typical wide-bodied commercial aircraft. The circumstances under which refrigeration is cost effective and the cost reduction achieved for various operational conditions are identified. Author

Section 5.
RELIABLE PACKAGING

A72-39766 **Packaging for the birds.** H W Markstein. *Electronic Packaging and Production*, vol 12, Aug 1972, p 28, 30, 33 (3 ff)

Review of some of the techniques currently used and contemplated for the protection of missile guidance electronics against the damaging effects of intense X rays and gamma radiation on electronic circuit materials and semiconductor performance from nuclear blasts of antiballistic missile detonations in the vicinity of oncoming ICBMs. Following a discussion of these damaging effects illustrated by photographs of circuitry before and after intense X ray exposure, packaging techniques are described that employ materials of low atomic number and high melting point, beryllium and magnesium interconnection systems, dielectric isolation for semiconductors, and overload resistors for dissipation of momentary power surges. The techniques described include a prototype stacked multilayer hybrid design, beam leaded interconnect packaging and standardized module design approaches M V E

A72-39768 **Avionics packaging and the new demands.** H W Markstein *Electronic Packaging and Production*, vol 12, Aug 1972, p 52, 54-56, 58

Review of some of the weight-saving, vibration-proofing, and heat-dissipating techniques used in avionics packaging. The electronic multiplexing packaging system proposed for the B-1 bomber is shown to make possible weight savings corresponding to the elimination of 33 miles of wire. To ruggedize the design and provide heat transfer this system involves an assembly of two circuit boards attached back to back on supporting rails. Rack-mounted and 'egg-crate' packaging techniques are also discussed M.V E

A73-35285 **The black box approach - Here to go.** J A Hastings (Lockheed-California Co., Burbank, Calif) In NAECON '73, Proceedings of the National Aerospace Electronics Conference, Dayton Ohio, May 14-16, 1973 New York, Institute of Electrical and Electronics Engineers, Inc , 1973, p 37-44

The conventional black box approach to packaging avionics is costly. It is costly not only in terms of excessive packaging weight, inefficient cooling, and multiplicity of hardware qualification programs, but use of the black box approach inhibits exploitation of new circuit technology, better component cooling and expanded employment of digital avionics. The solution to this problem is to adopt a revolutionary departure from the usual proliferation of black boxes. The approach taken is to modularize and consolidate the electronics packaging into relatively few compartments which, among other things, accommodates the advancing circuit technology and affords better cooling resulting in improved reliability (Author)

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Section 6.
LIFE CYCLE COST

N76-17331# Aerospace Guidance and Metrology Center, Newark Air Force Station Ohio

THREE LIFE CYCLE COST MODELS FOR INERTIAL SYSTEMS Final Report

Robert E Adel, William J Bonner, and Keith J Gibson 4 Apr 1974 50 p

(AD-A000483, AGMC 74-011-2) Avail NTIS CSCL 17/7

The purpose of this report was to present three different Life Cycle Cost models for inertial systems to the membership of the Life Cycle Cost Task Group of the Joint Services Data Exchange for Inertial Systems for the purpose of familiarization prior to the April 1974 meeting of that group in Anaheim, California. The report describes three life cycle cost models that have been used in economic analysis of inertial navigation systems Author (GRA)

A74-38582 **Life cycle cost comparisons of avionic system design alternatives.** P S Kilpatrick and A L Jones (Honeywell, Inc., Minneapolis, Minn.) In NAECON '74, Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 13-15, 1974 New York, Institute of Electrical and Electronics Engineers, Inc., 1974, p 514-520

A75-44219 **Cost of ownership - An overview: Life cycle costs - Evaluation of avionic system reliability improvements.** H A Brode (Hughes Aircraft Co., Canoga Park, Calif.) In Annual Reliability and Maintainability Symposium, Washington, D.C., January 28-30, 1975, Proceedings New York, Institute of Electrical and Electronics Engineers, Inc., 1975, p 212-216

A definition of life cycle cost is provided and an avionics life cycle cost model is presented. Two computer programs are utilized. One model generates development and investment phase costs. Another model computes operating and investment phase support costs. The output of both models is combined into one computer printout. Attention is given to the calculation of maintenance resource requirements, study ground rules and assumptions, and life cycle cost results. It is shown that it is possible to reduce the life cycle cost significantly G R

A75-44246 **A logistics analysis and ranking model /ALARM/** W L Davidson and B J Landstra (Hughes Aircraft Co., Canoga Park, Calif.) In Annual Reliability and Maintainability Symposium, Washington, D.C., January 28-30, 1975, Proceedings New York, Institute of Electrical and Electronics Engineers, Inc., 1975, p 538-542

ALARM is a support cost model useful for the following purposes: computation of life cycle support costs for a system composed of replaceable subassemblies, determination of the most cost effective of alternate design concepts, analysis of the sensitivity of support costs to changes in system design parameters, selection of the most economical of four specified maintenance concepts, identification of the highest cost components and support elements of a system. The model is complete and operational, and has been used effectively in the evaluation of support of a complex airborne avionics system. This model produces life cycle support cost information which is essential for evaluating approaches for maintaining an equipment system. This information is provided in clearly defined reports produced by the model on demand (Author)

Section 7.
CASE HISTORIES

N73-28960# Oklahoma City Air Materiel Area, Tinker AFB, Okla.
LOGISTIC PERFORMANCE DATA BOOK FOR A-7D BOMB NAVIGATION SYSTEM
Mar 1973 84 p refs
(AD-762215; A-7D-73000/73-1) Avail NTIS CSCL 15/5

The report presents the reliability, maintainability, logistic support cost, and general product performance information on the A-7D bomb navigation system. It's purpose is to impart sufficient logistics support history on the bomb navigation system to the engineering/design community represented by AFSC and the contractors engaged in the design of similar systems/sub-systems for Air Force use. Author (GRA)

A73-17617 # **The trend toward increasing avionics complexity.** R. C. Collins (United Air Lines, Inc., San Francisco, Calif.). *American Institute of Aeronautics and Astronautics, Annual Meeting and Technical Display, 9th, Washington, D.C., Jan. 8-10, 1973, Paper 73-28.* 4 p. Members, $1.50; nonmembers, $2.00.

'Avionics' is defined as those areas of application of electronics to aircraft where an impact on the operational safety or reliability is present. Aspects of redundancy are discussed which lead to the conclusion that excessive redundancy may complicate matters unnecessarily. Increasing complexity is the price that must be paid for increasing operational versatility. It is suggested that avionics components could be designed with a guaranteed operational life rather than a guaranteed mean time between failure. F.R.L.

A73-19403 **Calculation of the reliability of electronic components in an 'aeronautics' environment shaped by the operational service routines of onboard equipment devices used by Air France (Calcul de la fiabilité de composants électroniques dans l'environnement 'aviation' à partir du suivi d'exploitation d'équipements de bords utilisés par la compagnie Air-France).** D. Levy (CNET, Centre de Fiabilite, Bagneux, Hauts-de-Seine, France). In National Congress on Reliability, Perros-Guirec, Cotes-du-Nord, France, September 20-22, 1972, Text of the Lectures. Paris, Centre National d'Etudes des Télécommunications, 1972, p. 41-47. In French.

A73-33086 # **Cost-of-ownership design philosophy for inertial navigators.** R. L. Ringo (USAF, Avionics Laboratory, Wright-Patterson AFB, Ohio). *Astronautics and Aeronautics*, vol. 11, June 1973, p. 59-63.

The AN/ASN-101 gimbaled electrostatic gyro aircraft navigation system (GEANS) has from its inception been designed and developed to provide precision navigation with a low total-life-cycle cost. GEANS employs a unique gyro, the electrostatic gyro. Electrically suspended gyros inherently have exceptional performance characteristics. The GEANS technology base is discussed together with the design approach used, questions of the development technology, the target cost-structure, aspects of material cost, maintenance action, and physical characteristics. The AN/ASN-101 GEANS is now being optimized to both improve further its reliability and maintainability and further reduce its cost of ownership. G.R.

A73-37814 # **Guidance, control, and instrumentation progress on the McDonnell Douglas DC-10.** C. L. Stout (Douglas Aircraft Co., Long Beach, Calif.). *American Institute of Aeronautics and Astronautics and Gosudarstvennyi Komitet po Nauke i Tekhnike, USSR/US Aeronautical Technology Symposium, Moscow, USSR, July 23-27, 1973, Paper.* 14 p.

The design, development, testing, certification, and initiation of the present generation of jet transport systems into revenue service occurred through scheduled phases. Aspects of these phases as they pertain to the flight guidance and control, automatic thrust management, and area navigation systems of the DC-10 aircraft are discussed. Advances in systems capability and complexity in the wide body jet aircraft greatly increased the problems of flight test. Laboratory testing and simulation were used extensively to reduce flight test time requirements, and an advanced data acquisition and processing system was utilized to support the flight test program. F.R.L.

A74-20954 **Equipment procured reliability and real life survival.** O. Markowitz (US Navy, Aviation Supply Office, Philadelphia, Pa.). In Annual Reliability and Maintainability Symposium, Los Angeles, Calif., January 29-31, 1974, Proceedings. New York, Institute of Electrical and Electronics Engineers, Inc., 1974, p. 249-255. 6 refs.

Recommendations are made for improving communications between suppliers and users of equipment in the area of reliability. It is concluded that the hazards in real life equipment flow and end use do not compare to those inherent in equipment laboratory verification of failure rate. Thus any translation of laboratory or specified failure rate as a direct expectation of end use failure rate is inadequate. There is much needed in the way of the operator's understanding of what is required from contractors in the context of reliability and, as well, much is needed in contractor's understanding of the real life equipment flow and hazards of survival. T.M.

A74-38555 **Improving Mean Time Between Maintenance Actions - A recommended system approach.** R. C. Perdzock (USAF, Wright-Patterson AFB, Ohio). In NAECON '74; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 13-15, 1974. New York, Institute of Electrical and Electronics Engineers, Inc., 1974, p. 325-331.

A wide discrepancy continues to exist between Mean Time Between Failure (MTBF) for pieces of avionic equipment as determined from qualification tests and the Mean Time Between Maintenance Action (MTBMA) attained in operation. The present work discusses some of the probable causes for this discrepancy. Available data indicate that major strides can be made by improving Built In Test (BIT) and Aerospace Ground Equipment (AGE) design to assure that malfunctions are correctly diagnosed. It is urged that reliability testing and test of BIT and AGE capability be initiated as early in the design phase as possible. These tests should be carried out in stepwise fashion to allow a test-fix-test concept against increasingly difficult test requirements. P.T.H.

A75-27839 **Reliability life cycle of a complex electronic airborne equipment.** S. P. Mercurio (General Electric Co., Aerospace Equipment Div., Utica, N.Y.) and J. M. Black (USAF, Aeronautical Systems Div., Wright-Patterson AFB, Ohio). *IEEE Transactions on Reliability*, vol. R-24, Apr. 1975, p. 2-7.

A good reliability program through design and production results in excellent equipment performance in the field. A full life cycle under controlled failure reporting and analysis procedures is covered. An excess of 48,000 flight hours over 27,000 missions with 303 failures reported from five reporting maintenance shops constitutes the field reporting phase. In addition, details and supporting documentation of the overall reliability program during the design phase, demonstration phase, production phase and field use phase are presented. (Author)

A75-37679 **The F-4E digital scan converter - An example of reducing the life cycle cost of avionics through digital technology.** R. J. Jarvis (USAF, Avionics Laboratory, Wright-Patterson AFB, Ohio). In NAECON '75; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, June 10-12, 1975. New York, Institute of Electrical and Electronics Engineers, Inc., 1975, p. 451-456.

A digital scan converter (DSC) for the F-4E aircraft is described which provides a means of displaying radar information, attack symbology, and electrooptical sensor imagery, all on a common indicator. The discussion covers system description and principles of operation, two flight test results, and life cycle cost analysis for the reliability and maintainability of the DSC equipment. It is shown that DSC exhibits increased reliability, maintainability, and growth capability over the analog scan converter, while simultaneously providing equivalent operational performance. S.D.